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HIGH-PERFORMANCE MDMO-PPV FOR POLYMER-BASED LUMINESCENT SOLAR CONCENTRATORS IN SCALABLE ENERGY HARVESTING

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ABSTRACT

Luminescent solar concentrators (LSCs) have emerged as promising devices for enhancing solar energy harvesting by efficiently capturing and directing light onto photovoltaic cells. Among the diverse luminescent materials investigated, conjugated polymers stand out due to their tunable optical properties, solution-processability, and mechanical flexibility. Poly[2-methoxy-5-(3',7'-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV) exhibits a broad absorption spectrum and high photoluminescence quantum yield, exhibited a peak PLQY of 82%, positioning it as a strong candidate to address the limitations of previously studied polymer-based LSCs. Despite its advantageous optoelectronic characteristics, the use of MDMO-PPV in LSCs remains largely underexplored.

This study focuses on the fabrication and optical characterization of MDMO-PPV-based LSCs, evaluating their optical efficiency and benchmarking their performance against established polymeric systems. Key challenges in LSC optimization, such as reabsorption losses and limited Stokes shifts, are addressed through potential molecular engineering approaches and photonic design strategies. Optical performance characterization revealed a maximum optical power conversion efficiency of 2.73%, demonstrating significant improvement over previously reported polymer-based LSC systems. By systematically assessing the optical behavior of MDMO-PPV-based LSCs, this work aims to advance the development of high-efficiency, polymer-based LSCs and support their integration into next-generation photovoltaic technologies. The findings are expected to contribute valuable insights into the design of scalable, cost-effective, and efficient luminescent materials for renewable energy applications.

Keywords: Conjugated polymers, MDMO-PPV, Luminance solar concentrator, Reabsorption.

1 INTRODUCTION

The global pursuit of sustainable energy solutions has intensified interest in innovative photovoltaic technologies, with luminescent solar concentrators (LSCs) emerging as promising candidates for efficient and versatile solar energy harvesting. LSCs operate by embedding luminescent materials within a transparent waveguide, which absorbs incident sunlight, re-emits it at longer wavelengths, and channels the emitted photons toward the edges of the device, where photovoltaic (PV) cells convert them into electricity. This mechanism not only decouples light absorption from energy conversion but also enables lightweight, semi-transparent, and flexible solar harvesting platforms suitable for building-integrated photovoltaics (BIPV), wearable electronics, and portable power systems [1, 2].

Polymer-based LSCs, in particular, offer significant advantages due to their optical clarity, ease of processing, low weight, and compatibility with large-area fabrication [3]. Within this context, conjugated polymers have garnered increasing attention as efficient luminophores, owing to their strong visible-light absorption, large absorption cross-sections, high photoluminescence quantum yields, and tunable emission properties [4]. Cambié et al. demonstrated the use of luminophore-doped polymers in LSC-photomicroreactor systems, emphasizing their potential in photochemical applications and solar photon management [5]. In addition, spectral-based analysis of thin-film LSCs by Dienel et al. has underlined the importance of polymer matrices in reducing overall solar electricity cost [6].

However, many traditional conjugated polymers such as P3HT and MEH-PPV exhibit relatively narrow absorption bands and limited Stokes shifts, resulting in suboptimal light-harvesting and higher reabsorption losses [7]. To overcome these limitations, recent research has explored alternative polymer systems with enhanced optical and morphological properties. In particular, poly[2-methoxy-5-(3’,7’-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV) has emerged as a strong candidate due to its broader absorption window, high photoluminescence quantum yield, and excellent solution processability. Its compatibility with scalable techniques such as spin-coating and inkjet printing makes it highly suitable for large-area device fabrication [8-10].

Jo et al. have demonstrated that careful engineering of polymer matrices, such as EVA, doped with luminescent molecules can significantly enhance transparency and optical performance in LSCs [8]. Similarly, Li et al. proposed hybrid luminescent-scattering designs that combine conjugated polymers with scattering domains, improving light trapping and

overall efficiency [11]. These strategies underscore the importance of judicious material selection and architectural optimization in realizing high-performance devices.

Moreover, the integration of quantum dots, core/alloyed-shell nanostructures, and perovskite-based emitters into polymer matrices has further demonstrated the potential of multifunctional luminophores for LSCs [12-15]. However, issues such as stability, toxicity, or complex synthesis often limit their large-scale use. In contrast, MDMO-PPV offers a low-cost, solution-processable, and environmentally benign alternative, with demonstrated performance advantages in waveguiding and emission efficiency [16, 17].

In this study, we report the fabrication and optical characterization of MDMO-PPV-based LSCs. We systematically examine the effect of polymer concentration, film thickness, and substrate type on device performance metrics such as absorption efficiency, photoluminescence intensity, and waveguiding behavior. By benchmarking these results against other polymer-based LSC systems, our work seeks to highlight the practical advantages and fundamental potential of MDMO-PPV as a next-generation luminophore for scalable, efficient, and sustainable luminescent solar concentrators.

2 MATERIAL AND METHOD

2.1 Fabrication of MDMO-PPV-Based Luminescent Solar Concentrators (LSCs)

Poly (lauryl methacrylate) (PLMA) was selected as the host matrix due to its excellent optical transparency in the visible spectrum and its ability to minimize aggregation of the MDMO-PPV luminophore through steric stabilization, facilitated by its long alkyl side chains. To prepare the luminophore-doped precursor, 10 mg of MDMO-PPV was dispersed in 2 mL of PLMA under an inert nitrogen atmosphere inside a glovebox to prevent oxidative degradation. The photopolymerizable host resin was formulated by combining 0.25 wt% diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (TPO) as a UV-sensitive photoinitiator, 20 wt% ethylene glycol dimethacrylate (EGDMA) as a crosslinking monomer, and 80 wt% lauryl methacrylate (LMA) as the primary monomer. The resulting mixture was homogenized under light-free conditions for 4 hours to ensure uniformity and suppress premature photoinitiation. Following 23 OD dispersion, the MDMO-PPV solution was integrated into 34.5 mL of the pre-formulated host matrix and stirred continuously for a minimum of 6 hours in a light-shielded Falcon tube to ensure thorough mixing and homogeneous luminophore distribution.

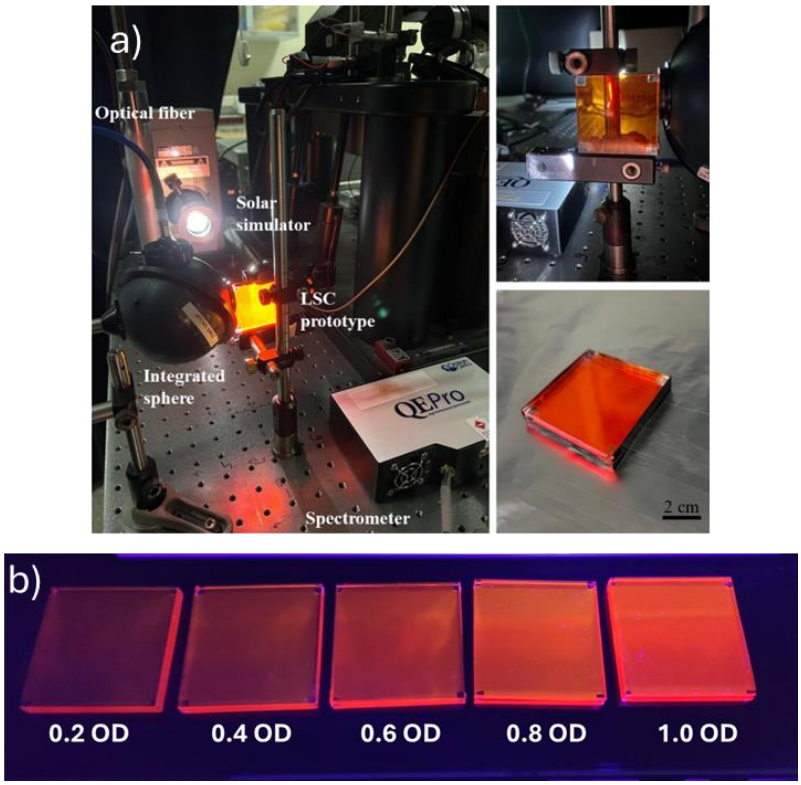

Figure 1. a) Photographs of the power measurement of LSCs leaned to the integrated sphere and of the LSC prototype covered with black tape around three edges (bottom right corner). b) Photographic images of MDMO-PPV-based LSCs fabricated with varying luminophore concentrations, showing uniform coloration and optical quality.

Waveguide structures for LSC devices were fabricated by assembling two borosilicate glass substrates (each 3 mm thick) using optically transparent acrylic adhesive tape, thereby creating a hermetically sealed cavity. Prior to filling, the internal cavity was purged with nitrogen gas to eliminate residual oxygen, which could inhibit radical polymerization during UV curing. The luminophore-containing resin was injected into the cavities using a hypodermic syringe, with MDMO-PPV concentrations precisely controlled relative to the host matrix composition. Immediately after filling, the devices were irradiated with uniform 365 nm UV light for 20 minutes to initiate photopolymerization, resulting in in situ crosslinking of the polymer matrix. The finalized LSCs had lateral dimensions of 50 mm × 50 mm with a total thickness of 7 mm and exhibited broadband absorption across the visible range, imparting a characteristic orange hue due to the MDMO-PPV emission (Fig. 1a and 1b).

2.2 Characterization of MDMO-PPV-Based Luminescent Solar Concentrators (LSCs)

Following fabrication, the optical performance of the MDMO-PPV-based LSCs was evaluated through power conversion efficiency (η_{power}) measurements using an integrating sphere setup. The integrating sphere was coupled to a calibrated photodetector via an optical fiber, with precise lateral and vertical alignment to ensure reproducibility and minimize geometrical errors during measurement. To assess the LSC output, the device was positioned at the entrance port of the integrating sphere, and the emitted power was quantified under illumination. The absolute power output of the device was determined by calculating the ratio of collected edge-emitted power to the total incident power, based on pre-calibrated power density values. To minimize errors from waveguided light leakage and external reflections, three sides of the LSC were covered with black, non-reflective tape, exposing only one output edge for photon collection. Since the optical fiber interfaced with only half of the exposed waveguide edge, the recorded emission was scaled by a factor of eight to account for the total guided emission across all device edges under ideal symmetrical conditions. This approximation enables a comprehensive estimate of the total photonic output of the concentrator. For illumination, a Newport 67005 quartz tungsten-halogen arc lamp was employed as the excitation source. The emission spectrum of the lamp was spectrally matched and intensity-calibrated against the standard AM 1.5G solar spectrum to ensure relevant and comparable solar simulation conditions. The fluorescence spectrometer (Cary Eclipse), UV-Vis spectrometer (Cary 100), Keithley 3200 SCS used for optical characterizations.

3 RESULTS AND DISCUSSION

Figure 2 presents the UV–Vis absorption and photoluminescence (PL) spectra of MDMO-PPV in solution, elucidating its key optical properties relevant to luminescent solar concentrator (LSC) applications. The absorption spectrum displays a broad band spanning approximately 400–550 nm, with a pronounced peak centered around 470 nm, corresponding to π–π* electronic transitions along the conjugated polymer backbone [9]. This broad absorption profile facilitates efficient harvesting of a significant portion of the visible solar spectrum.

The PL spectrum reveals a dominant emission peak at ~590 nm, yielding a substantial Stokes shift of ~120 nm. The Stokes shift is the energy difference between absorption and emission maxima, which is pivotal on the degree reabsorption of fluorescence photons by the

emitter, hence determines the fluorescence spectrum [18, 19] This large spectral separation between absorption and emission is a critical advantage for LSCs, as it significantly reduces the likelihood of reabsorption, one of the primary loss mechanisms in waveguide-based devices [14, 16]. The reabsorption is the phenomenon dependent on the overlap of absorption and emission spectra of emitters, where the overlapped portion of the emission spectrum is reabsorbed by the emitter. Since the reabsorbed high energy photons are emitted back with initial emission spectrum, the final spectrum becomes red shifted and the intensity on high energy part of the spectrum vanishes[19, 20]. The minimal spectral overlap between the absorption and emission bands indicates that MDMO-PPV can sustain high photoluminescence efficiency while maintaining effective photon waveguiding.

These optical characteristics are consistent with prior reports on conjugated polymers in LSC configurations [10], further supporting the suitability of MDMO-PPV as a luminophore. Moreover, the emission falls within the spectral window where common transparent substrates such as PMMA and glass exhibit minimal optical attenuation, thereby promoting efficient light propagation toward the device edges and enhancing the power output of edge-mounted photovoltaic cells. Under ambient light, a gradual increase in coloration is observed as the polymer concentration increases, indicating uniform dispersion within the host matrix. When exposed to UV light, all samples exhibit strong and uniform photoluminescence across the surface, with emission intensity visibly increasing with polymer loading.

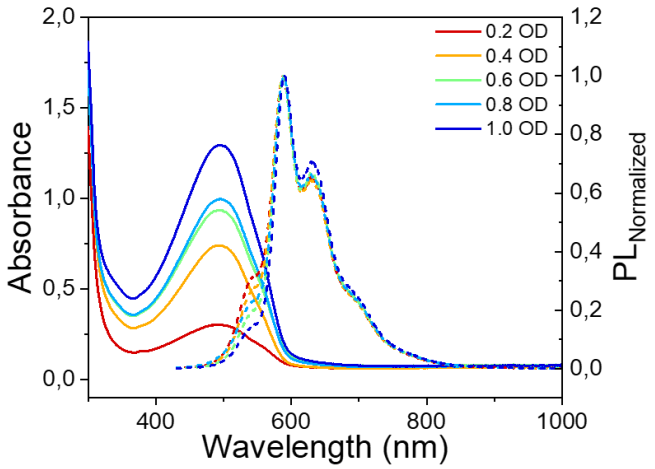

Figure 2. Absorbance spectra (left panels) and photoluminescence spectra (right panels) of LSCs obtained by photopolymerization with respect to the MDMO-PPV luminophore concentration.

The homogeneous emission under UV excitation suggests that phase separation or aggregation of MDMO-PPV is minimal, which is essential to prevent scattering losses and optical inhomogeneities. This observation also implies that the fabrication method employed, likely based on solution processing and spin- or drop-casting techniques, yields optically smooth and continuous films. From an application perspective, this visible and strong luminescence demonstrates the capability of MDMO-PPV to absorb short-wavelength light and efficiently re-emit it at longer wavelengths, supporting its utility in enhancing the performance of planar LSC devices. Furthermore, the color purity and brightness indicate a potentially high photoluminescence quantum yield (PLQY), though quantitative PLQY measurements would be necessary for a more complete assessment.

Figure 3a compares the spectral emission profiles collected from the edges of LSCs with different MDMO-PPV loadings. While the peak position remains stable (~590 nm), consistent with the intrinsic PL of MDMO-PPV, the intensity varies noticeably. Maximum edge emission is achieved at an intermediate concentration, suggesting an optimal balance between absorption and waveguiding efficiency. At higher concentrations, reabsorption and self-quenching likely reduce the net photon output [4].

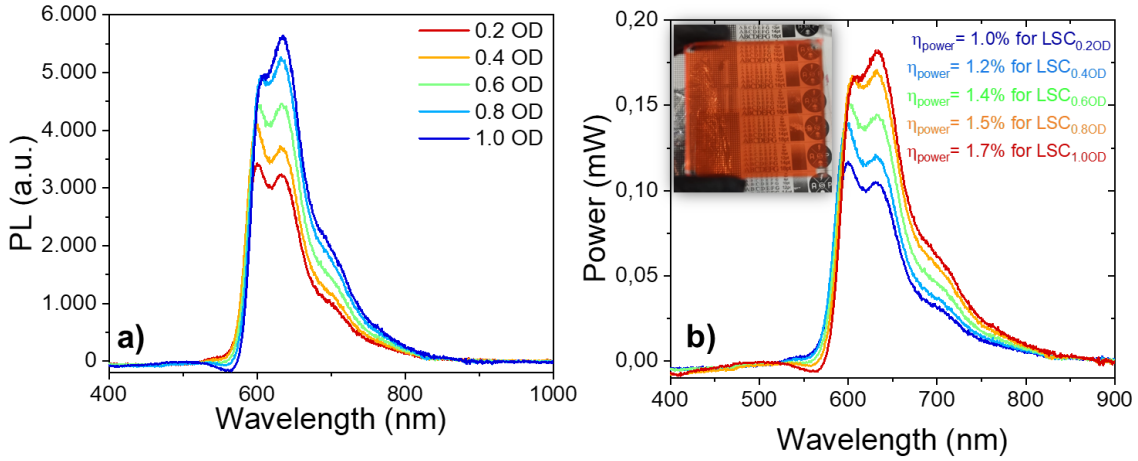

Figure 3. a) PL spectra of the MDMO-PPV b) power measurements of MDMO-PPV based LSCs, transparent LSC prototype (top left corner).

Figure 3b displays the irradiance measured at the edge of MDMO-PPV-based LSC devices under simulated AM1.5G solar illumination. As the dye concentration increases, the edge-irradiated intensity also rises, indicating more effective light absorption and waveguiding of re-emitted photons.

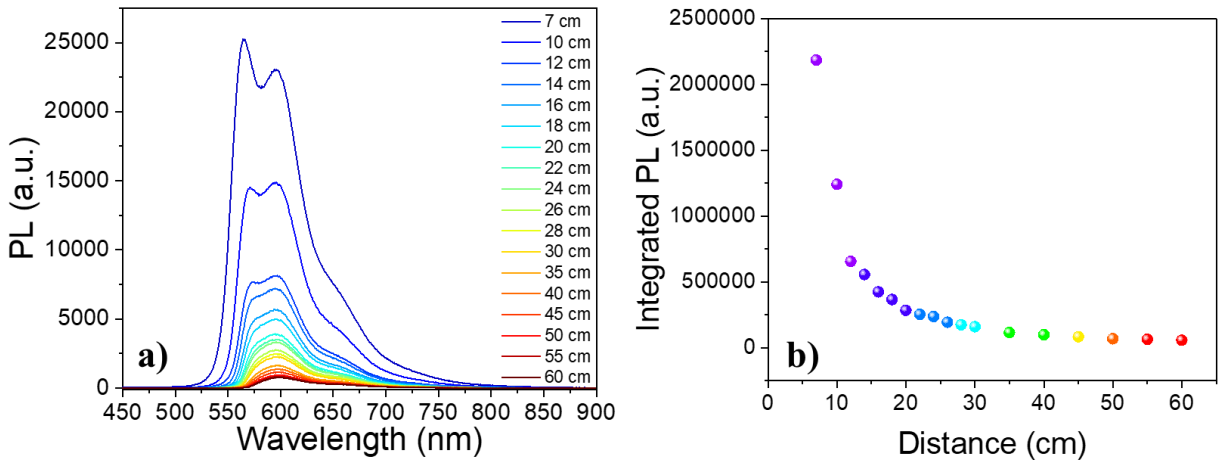

Figure 4. a) PL emission spectra as a function of the wavelength and b) integrated PL emission spectra as a function of the wavelength excitation distance for 0.8 OD MDMO-PPV based LSCs.

This relationship confirms that higher polymer content improves the photonic capture and transport capacity of the LSC. However, the nonlinear growth beyond a certain concentration implies the onset of optical saturation and possible reabsorption or concentration quenching effects [17]. These results underline the importance of concentration optimization in LSC design. While increasing dye content enhances absorption, excessive loading can diminish device performance due to non-radiative losses or photon trapping. The data confirm that MDMO-PPV enables strong edge-guided emission and can be effectively employed as a luminophore in planar LSC configurations, provided that the dye concentration is appropriately tuned.

To assess the extent of reabsorption within the LSCs, spatially resolved PL measurements were performed by varying the excitation position relative to the device edge. As shown in Figure 4a, PL emission intensity decreases as the excitation point moves further from the edge. This decay indicates the cumulative effects of photon reabsorption and waveguide losses, such as scattering or escape through the top and bottom surfaces. To quantify this behavior, the integrated PL intensity was plotted as a function of excitation distance (Figure 4b). Figure 4b presents the photoluminescence (PL) intensity collected from the edge of the LSC under uniform excitation. This measurement was performed by placing the excitation source on the top surface of the LSC while collecting the emission from the side edge using a fiber-coupled spectrometer. The edge PL represents the waveguided emission that reaches the edges after internal reflection. To ensure uniformity, the excitation beam was expanded and homogenized to cover the full surface area of the LSC. The exponential attenuation profile confirms that a significant fraction of emitted photons is lost before reaching the device edge,

primarily due to reabsorption by the MDMO-PPV luminophore. These findings reinforce the importance of employing luminophores with large Stokes shifts and optimizing dye concentration to minimize spectral overlap and internal reabsorption losses, both of which are essential for maximizing LSC efficiency. The luminescent solar concentrator (LSC) devices incorporating MDMO-PPV with high photoluminescence quantum yield (PLQY) exhibit the highest power conversion efficiency (η_{power}) of 2.73%. A high PLQY signifies that a larger fraction of absorbed photons is re-emitted as photoluminescence, thereby increasing the amount of light redirected toward the solar cells located at the edges of the LSC. This efficient photon recycling significantly boosts the power output. Moreover, a high PLQY mitigates reabsorption losses, wherein re-emitted photons are reabsorbed by other luminophores within the waveguide. Such reabsorption not only attenuates the overall photon flux reaching the solar cells but also leads to spectral red-shifting and energy dissipation. By minimizing these losses, high-PLQY luminophores preserve photon intensity during waveguiding, enhancing light transport and maximizing photonic utilization. Therefore, achieving high quantum yield is critical for optimizing photoluminescence efficiency, minimizing optical losses, and ultimately improving the overall performance and power conversion efficiency of LSCs.

4 CONCLUSION

In this study, the fabrication, photophysical characterization, and performance evaluation of MDMO-PPV-based luminescent solar concentrators (LSCs) were systematically investigated. MDMO-PPV exhibits a broad absorption profile and a substantial Stokes shift of approximately 120 nm, rendering it a promising candidate for minimizing reabsorption losses and enabling efficient photon waveguiding in planar LSC architectures. Photoluminescence imaging under ultraviolet excitation confirmed uniform film morphology and robust emission characteristics across a range of polymer concentrations. Quantitative edge emission measurements conducted under simulated AM1.5G solar illumination revealed that LSC performance is highly dependent on the concentration of the luminophore. While increased MDMO-PPV content enhances light absorption and subsequent emission, excessive dye loading results in deleterious effects such as self-quenching and reabsorption, thereby diminishing the net photon output reaching the waveguide edges. These findings underscore the critical importance of concentration optimization in maximizing the optical efficiency of LSC devices. Long-term photostability assessments demonstrated negligible degradation in edge-emitted photoluminescence under continuous illumination, indicating the photochemical

stability of MDMO-PPV when embedded within an appropriate host matrix. Additionally, a schematic representation of the waveguiding mechanism was provided to elucidate the fundamental operational principles of LSCs and to highlight intrinsic loss channels. Overall, the results validate MDMO-PPV as a viable, low-cost, and solution-processable luminophore for scalable LSC technologies. With further refinement in material engineering and encapsulation strategies, such polymer-based LSCs hold considerable promise for integration into building-integrated photovoltaics (BIPV) and other solar energy harvesting platforms.

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Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

Artificial Intelligence (AI) Contribution Statement

This manuscript was entirely written, edited, analyzed, and prepared without the assistance of any artificial intelligence (AI) tools. All content, including text, data analysis, and figures, was solely generated by the authors.

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