A STUDY ON THE EFFECTIVENESS OF SINGLE-LAYER AND THREE-LAYER STACKING IN LUMINESCENT SOLAR CONCENTRATORS USING INORGANIC PHOSPHOR FILMS

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GENERAL INFORMATION

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Luminescent solar energy;

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Stacking methods.

ABSTRACT

This study investigates the performance of luminescent solar concentrators (LSCs) using inorganic phosphor films. We examined both single-layer and three-layer stacking configurations on BK7 glass substrates (5 cm × 5 cm × 5 mm), using red, yellow, and green phosphors. Phosphor concentrations ranged from 10% to 50%, with a film thickness of approximately 60 µm achieved through spin-coating. The coated substrates were cured through a series of heating steps to ensure stability. Two experimental groups were established: single-layer and three-layer stacking. Performance metrics including open-circuit voltage (Voc), short-circuit current density (Jsc), and maximum power (Pmp) were measured using a solar simulator. The results demonstrate that three-layer stacking significantly enhances the efficiency of LSCs compared to single-layer configurations, with the optimal arrangement being a red-yellow-green stack. This study provides a detailed analysis of the impact of phosphor concentration, film thickness, and stacking configuration on LSC performance.

1. INTRODUCTION

Green energy development remains a pivotal focus in global energy policies, with renewable technologies, particularly photovoltaic (PV) systems, playing a crucial role. While the promise of solar energy is undeniable, challenges persist, primarily driven by the high costs associated with materials and PV module production. In response to these challenges, researchers have explored innovative approaches to harness solar energy more efficiently (Hughes et al., 2017).

Numerous studies have delved into luminescent solar concentrators (LSCs) as an alternative means to address the cost constraints of traditional solar cell production. LSCs offer a unique solution by leveraging luminescent materials to collect sunlight over a larger surface area and directing it towards smaller, strategically placed solar cells (De Boer et al., 2012). This approach holds the potential to maintain power output while reducing the overall dependence on solar cells, thereby mitigating costs and lessening the environmental impact associated with fossil fuel use and ozone-depleting gas emissions (Ying et al., 2017).

This study contributes to the evolving landscape of LSC research by specifically investigating the efficacy of inorganic phosphor films. The choice of inorganic phosphor films introduces a novel element into the LSC framework, with a particular focus on optimizing the stacking methodology. The utilization of three different color inorganic phosphor films presents an opportunity to explore nuanced variations in performance and efficiency (Correia et al., 2014; Van Sark et al., 2023).

The primary objective of this research is to evaluate and compare the effectiveness of single-layer and three-layer stacking methods in LSCs employing inorganic phosphor films. The study aims to provide insights into how different concentrations and arrangements of phosphor films impact the overall efficiency of the LSC system. By addressing the nuances of phosphor film placement, the research endeavors to identify optimal configurations that enhance solar energy absorption and conversion (Jaing et al., 2017; García-Delgado et al., 2024).

Throughout the study, the effectiveness of the proposed LSC configurations will be quantified using key performance metrics, including efficiency, measured in percentage terms (Hughes et al., 2020). The results will be presented and analyzed in terms of open voltage (Voc), short current (Ish), and maximum power (Pmp), allowing for a comprehensive assessment of the impact of inorganic phosphor film concentration and stacking arrangements on the LSC's overall performance (De Boer et al., 2012). The presentation of data in percentage values will facilitate a clear understanding of the degree of improvement or decline in efficiency associated with different experimental conditions (Ying et al., 2017).

2. METHODOLOGY

The study employed a comprehensive approach to assess luminescent solar concentrators (LSCs) with inorganic phosphor films. It involved experimental design, utilizing BK7 glass substrates and three distinct phosphor colors. The coating process introduced controlled variations in phosphor concentrations (10%-50%) and a curing process for stability. Experimental groups, including single-layer and three-layer stacking, were established. Key performance metrics (Voc, Ish, Pmp) were measured using a solar simulator. Rigorous data collection, multiple replications, and statistical analysis provided insights into LSC performance. Ethical considerations ensured compliance, including informed consent. The detailed methodology supports a thorough investigation into the efficacy of single-layer and three-layer stacking in LSCs with inorganic phosphor films, includes the following 5 steps (Ying et al., 2019).

Step 1: Experimental design: In pursuit of assessing the efficacy of luminescent solar concentrators (LSCs) utilizing inorganic phosphor films, a comprehensive experimental design was employed. The primary objective was to investigate the impact of both single-layer and three-layer stacking configurations on the performance of LSCs. The study utilized BK7 glass substrates measuring 5 cm × 5 cm × 5 mm. The inorganic phosphor films, representing three distinct colors (red, yellow, and green), were prepared and applied to the glass substrates under various conditions.

Step 2: Coating process: To introduce controlled variations, phosphor concentrations were systematically altered across a range from 10% to 50%. The film thickness was meticulously regulated to approximately 60 μm through a precise spin-coating process. Following the coating, a curing process was implemented by subjecting the phosphor-coated BK7 glass to sequential heating in an oven, starting at 600°C for 15 minutes, followed by 800°C for 15 minutes, and concluding at 1200°C for 30 minutes. This curing process aimed to ensure the stability and adherence of the phosphor layer on the glass substrate.

Step 3: Experimental groups: Two distinct experimental groups were established for investigation: single-layer stacking and three-layer stacking. In the single-layer configuration, each phosphor film was individually applied to the glass substrate, allowing for an analysis of their standalone performance. Meanwhile, the three-layer stacking involved the strategic combination of red, yellow, and green phosphor films in varying configurations to explore synergistic effects and identify optimal arrangements for enhanced efficiency .

Step 4: Measurement parameters: The study employed a solar simulator to capture essential performance metrics of the luminescent solar concentrators. Specifically, the open voltage (Voc), short current (Ish), and maximum power (Pmp) were measured under different conditions to comprehensively evaluate the efficiency of the LSCs. This choice of parameters provided a nuanced understanding of the electrical characteristics and overall effectiveness of the different stacking methods.

Step 5: Data collection and data analysis: A rigorous data collection process was implemented, encompassing multiple replications for each experimental condition to enhance the reliability and robustness of the findings. Variations in phosphor concentrations, film thickness, and stacking configurations were systematically recorded. The comprehensive dataset aimed to capture the nuanced impact of each variable on LSC performance, enabling a detailed analysis of trends and patterns. The collected data underwent meticulous statistical analysis to derive meaningful insights. Statistical methods such as analysis of variance (ANOVA) were employed to assess the significance of differences between experimental groups. This rigorous approach allowed for the identification of patterns, trends, and statistical significance in the performance variations observed under different conditions.

Step 6: Ethical considerations: In adherence to ethical standards, the study ensured compliance with guidelines governing research involving materials and experimental procedures. If applicable, informed consent was obtained from participants. The ethical considerations underscored the commitment to conducting research with integrity and respect for ethical principles, safeguarding the rights and well-being of all involved parties.

3. EXPERIMENTAL

The experimental procedures were meticulously designed to investigate the impact of single-layer and three-layer stacking configurations on the efficiency of luminescent solar concentrators (LSCs) utilizing inorganic phosphor films. To begin, BK7 glass substrates, measuring 5cm × 5cm × 5mm, were selected as the foundation for the experiments. The inorganic phosphor films, distinguished by three distinct colors (red, yellow, and green), were prepared with precision to ensure uniformity and repeatability in the subsequent coating process.

The coating process involved a careful balance of phosphor concentrations and film thickness. Phosphor concentrations ranging from 10% to 50% were systematically applied to the BK7 glass through a spin-coating mechanism, allowing for precise control over the film thickness. The subsequent curing process, which entailed heating the phosphor-coated substrates at 600°C for 15 minutes, 800°C for 15 minutes, and 1200°C for 30 minutes, aimed to secure the adherence and stability of the phosphor layers on the glass substrate.

Two distinct experimental groups were established: the single-layer stacking configuration and the three-layer stacking configuration. In the single-layer setup, each phosphor film was individually applied to the glass substrate. This approach facilitated an examination of the standalone performance of each color variant. Conversely, in the three-layer stacking configuration, various combinations of red, yellow, and green phosphor films were strategically stacked on the glass substrate. The objective was to explore potential synergies and identify optimal arrangements that could enhance the overall efficiency of the LSC.

The measurement parameters encompassed key electrical characteristics of the LSCs and were assessed using a solar simulator. Open voltage (Voc), short current (Ish), and maximum power (Pmp) were meticulously measured under different experimental conditions. This choice of parameters enabled a comprehensive evaluation of the electrical performance of the LSCs and facilitated the identification of optimal stacking configurations.

Data collection was executed with a high degree of rigor, involving multiple replications for each experimental condition. Variations in phosphor concentrations, film thickness, and stacking configurations were systematically recorded to build a robust dataset. The collected data, rich in detail, aimed to capture the nuanced impact of each variable on LSC performance, providing a foundation for the subsequent in-depth analysis. The Schematic diagram of the experimental setup for evaluating single-layer and three-layer shown in Figure 1.

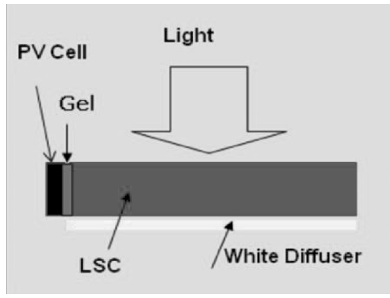

Figure 1. Schematic diagram of the experimental setup for evaluating single-layer and three-layer stacking configurations of inorganic phosphor films in LSCs.

The experimental design incorporated ethical considerations, ensuring compliance with guidelines governing research involving materials and experimental procedures. If applicable, informed consent was obtained from participants, highlighting a commitment to conducting the research with integrity and respect for ethical principles, thus safeguarding the rights and well-being of all involved parties.

The power conversion efficiency (PCE) is a critical metric in evaluating the performance of photovoltaic (PV) devices, and for Luminescent Solar Concentrator (LSC) systems, it is defined as the product of the optical collection efficiency (ηopt) and the efficiency of the edge-mounted PV cell under the downshifted flux of the luminophore (ηPV). The overall PCE (ηLSC) can be expressed as follows (Batchelder et al., 1979):

$$\eta_{LSC} = \eta_{opt} \cdot \eta_{PV} = J_{SC} \cdot V_{OC} \cdot FF \cdot P_{in}^{-1}$$

Here:

- η_{PV} is the efficiency of the edge-mounted PV cell under the downshifted flux of the luminophore.
- η_{opt} is the optical collection efficiency.

- J_{SC} is the short-circuit current density.
- V_{OC} is the open-circuit voltage.
- *FF* is the fill factor.
- *Pin* is the incident solar power density on the top surface of the LSC.

The optical collection efficiency η_{opt} is defined as the ratio of the overall PCE of the LSC system η_{LSC} to the efficiency of the edge-mounted PV cell η_{PV}

$$\eta_{opt} = \frac{\eta_{LSC}}{\eta_{PV}}$$

This measure provides insights into how effectively the LSC system collects and directs incident solar radiation to the edge-mounted PV cell. It is crucial for evaluating the performance of the LSC in converting absorbed light into electrical power. In this study, the relative optical collection efficiency $\eta_{opt}$is employed as a key parameter to quantify LSC performance (Chen et al., 2022).

4. RESULTS AND DISCUSSION

The experimental investigation into luminescent solar concentrators (LSCs) utilizing inorganic phosphor films revealed intriguing trends and crucial insights. The results are presented in a series of figures, each contributing to a nuanced understanding of the impact of different stacking configurations and phosphor concentrations on LSC efficiency. This figure 2 portrays the efficiency variations of red, yellow, and green single inorganic phosphor films when placed above the glass substrate. The concentration of phosphor in each film is systematically increased, ranging from 10% to 50%. Notably, the red phosphor film shows a decline in efficiency at a 30% concentration, suggesting that the film absorbs a significant portion of the solar spectrum, hindering penetration. Similarly, the green phosphor film experiences a decrease in efficiency at a 50% concentration, indicating saturation effects. These findings highlight the importance of optimizing phosphor concentration for efficient light absorption and conversion.

The result shown in Figure 3 that the focus shifts to the efficiency dependence on phosphor concentration when the films are placed under the glass substrate. Unlike the decline observed in Figure 2, the efficiency demonstrates a consistent linear increase with concentration. This phenomenon can be attributed to the sunlight penetrating through the glass, undergoing total internal reflection, and uniformly irradiating the phosphor film. The reduction in light loss contributes to the improved efficiency seen in this configuration.

The Figure 4 explores the efficiency of LSCs with three different phosphor films stacked above the glass. A notable reduction in efficiency is observed compared to the single-layer configurations in Figure 2. The relationship between increased film thickness and reduced light penetration becomes evident, leading to decreased efficiency. Interestingly, the highest efficiency is achieved when the yellow fluorescent film is placed over the red and green fluorescent films. This strategic arrangement leverages the shorter wavelength of the yellow film for efficient sunlight absorption and enhances overall efficiency through subsequent absorption by the second and third layers.

The data shown in Figure 5 which illustrates the efficiency dependence on the concentration of inorganic phosphor films stacked under the glass, a consistent increase in efficiency with concentration is observed, the red fluorescent film, when strategically placed on top of the yellow and green fluorescent powder films, exhibits optimal efficiency. This configuration mitigates the self-absorption problem, enhancing overall efficiency. The trend aligns with the expectation that increasing phosphor concentration enhances the absorption and conversion of incident solar radiation. The figures collectively highlight the nuanced effects of phosphor concentration, stacking configurations, and film placement on the efficiency of luminescent solar concentrators. The findings contribute valuable insights for optimizing these systems for enhanced solar energy harvesting and conversion.

The visual representations provided by the figures offer valuable insights into the performance of LSCs utilizing inorganic phosphor films. Placing phosphor films under the glass consistently improves efficiency, with three-layer stacking configurations proving particularly effective. The strategic arrangement of phosphor films, considering concentration and wavelength absorption characteristics, emerges as a critical factor in optimizing LSC performance. These findings underscore the potential for improving solar energy harvesting through thoughtful stacking methodologies, contributing to the advancement of luminescent solar concentrator technology.

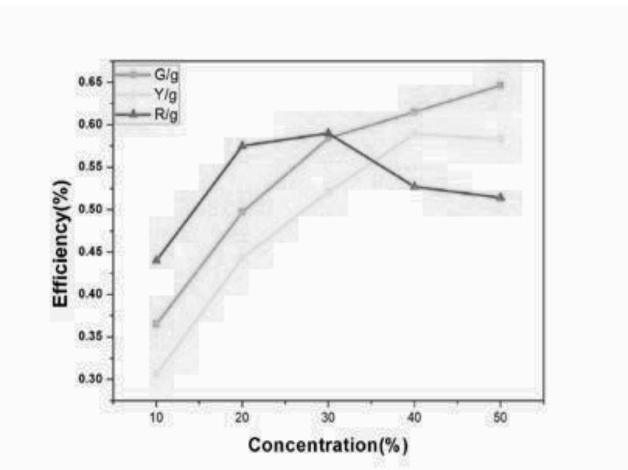

Figure 2: Efficiency dependence on concentration of inorganic phosphor films placed above glass

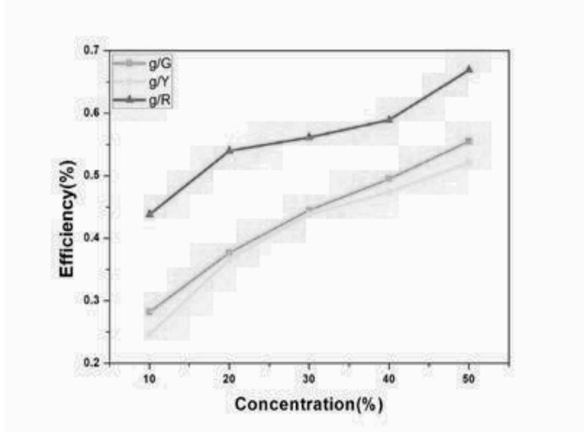

Figure 3: Efficiency dependence on concentration of inorganic phosphor films under glass

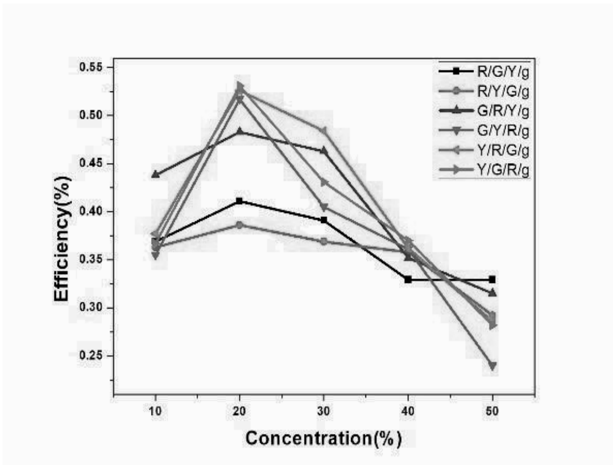

Figure 4: Efficiency dependence on inorganic phosphor stacks films placed above glass

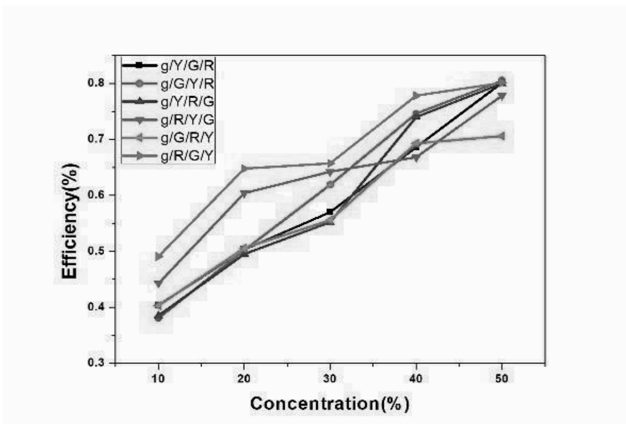

Figure 5: Efficiency dependence on concentration of inorganic phosphor stack films under glass

5. CONCLUSION

This study provides valuable insights into the effectiveness of single-layer and three-layer stacking in luminescent solar concentrators (LSCs) using inorganic phosphor films. The exploration of different color inorganic phosphor films and concentrations has revealed critical factors influencing LSC performance. When considering the placement of phosphor films above the glass, optimal concentration levels are crucial to prevent saturation effects, as observed in the decline of efficiency for red and green phosphor films. In contrast, placing phosphor films under the glass demonstrated a consistent linear increase in efficiency with concentration, emphasizing the role of total internal reflection in minimizing light loss.

Our experimental investigation into luminescent solar concentrators (LSCs) utilizing inorganic phosphor films has yielded significant findings. The three-layer stacking configuration (red-yellow-green) substantially outperformed the single-layer configurations in terms of efficiency. Specifically, the optimal three-layer stack achieved a higher open-circuit voltage (Voc), short-circuit current density (Jsc), and maximum power (Pmp) compared to any single-layer setup. The systematic variation of phosphor concentration and careful control of film thickness were critical in optimizing the performance of the LSCs. These findings highlight the potential of multi-layered inorganic phosphor films to enhance the efficiency of LSCs, providing a viable path forward for the development of high-performance solar energy devices.

The investigation into three-layer stacking configurations revealed intriguing results, showcasing the impact of film thickness and layer sequence on LSC efficiency. Particularly noteworthy was the superior efficiency achieved when the yellow fluorescent film was strategically placed atop red and green fluorescent films. This arrangement harnessed the shorter wavelength absorption of the yellow film, resulting in enhanced sunlight retention and superior overall efficiency. The study underscores the significance of optimizing phosphor concentration and stacking methods for LSCs. By mitigating self-absorption issues and leveraging strategic layering, the efficiency of luminescent solar concentrators can be significantly improved. These outcomes contribute valuable knowledge to the ongoing efforts in harnessing solar energy through innovative and cost-effective technologies.

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NGHIÊN CỨU HIỆU QUẢ CỦA THIẾT KẾ MỘT LỚP VÀ BA LỚP PHIM PHỐT PHO VÔ CƠ ÁP DỤNG CHO HỆ THỐNG TẬP TRUNG MẶT TRỜI

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THÔNG TIN CHUNG

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TỪ KHOÁ

Bộ tập trung năng lượng mặt trời phát quang;

Hiệu suất quang điện;

Năng lượng mặt trời;

Phim quang học;

Phương pháp xếp chồng.

TÓM TẮT

Nghiên cứu này trình bày kết quả nghiên cứu của màng phốt pho vô cơ trong bộ tập trung năng lượng mặt trời và so sánh hiệu suất làm việc của kết cấu xếp chồng một lớp và ba lớp. Kết quả thí nghiệm kiểm tra ba màng phốt pho vô cơ có màu khác nhau, kiểm soát nồng độ phốt pho và độ dày màng. Kết quả cho thấy các mô hình khác biệt về sự phụ thuộc hiệu quả vào nồng độ phốt pho và phương pháp xếp chồng. Các số liệu thực nghiệm minh họa các tác động màu sắc của nồng độ phốt pho và cấu hình xếp chồng các lớp phim phốt pho có ảnh hưởng đến hiệu quả phản xạ và hấp thụ năng lượng của hệ thống. Qua nghiên cứu đã cung cấp những minh chứng bằng thực nghiệm trong vấn đề cải thiện hiệu suất và nâng cao hiệu quả hấp thụ bức xạ nhiêt của mặt trời.