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Synthesis, Structural Characterization, and Luminescent Properties of Eu^{3+}-Doped Silicate-Based Red Light-Emitting Phosphor for LED Applications

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Abstract **Original Research Article**

This research investigates the synthesis and characterization of Eu^{3+}-doped silicate phosphors for use in red-emitting LEDs. These phosphors were synthesized through a high-temperature solid-state reaction method, a technique known for producing stable, crystalline phosphor materials. The structural and luminescent properties were thoroughly analyzed using techniques such as X-ray diffraction (XRD) to confirm crystallinity, photoluminescence (PL) spectroscopy to assess emission profiles, and scanning electron microscopy (SEM) for morphological examination. Results showed a prominent red emission peak at 611 nm due to the $^5D_0 \rightarrow {}^7F_2$ transition, which was optimized at a dopant concentration of 7 mol% Eu^{3+}. The phosphors also displayed excellent thermal stability, retaining over 85% of their luminescent intensity at 150°C, which is promising for applications in high-temperature LED systems. Additionally, optical properties, including Judd-Ofelt intensity parameters and stimulated emission cross-sections, were analyzed to further confirm these materials' suitability for photonic applications.

Keywords: Eu^{3+}-doped silicate phosphor, red emission, photoluminescence, X-ray diffraction, LED applications, thermal stability, concentration quenching, solid-state synthesis, Judd-Ofelt analysis, optical properties.

1.INTRODUCTION

In the transition toward energy-efficient lighting, light-emitting diodes (LEDs) have emerged as one of the most promising technologies, offering numerous advantages, including high energy efficiency, longevity, and minimal environmental impact. However, creating high-quality white light with LEDs requires a combination of red, green, and blue emissions to achieve the desired color rendering. Traditionally, red-emitting phosphors such as Y_2O_3
$^{3+}$ have been employed to supply the red component. However, these materials often suffer from reduced efficiency and thermal stability, which limits their effectiveness in LED devices [1].
Silicate-based phosphors, which possess favorable thermal and chemical stability, have garnered attention as potential replacements due to their ability to maintain luminescent properties even under high-temperature conditions. Rare-earth ions, particularly trivalent europium (Eu^{3+}), are commonly used as dopants in these materials. Eu^{3+} ions are especially valuable for red emission, as they display characteristic luminescent transitions, such as the $^5D_0 \rightarrow {}^7F_2$ transition, which emits in the red spectral range around 611 nm. This study aims to synthesize Eu^{3+}-doped silicate phosphors and examine their structural and luminescent properties, with a focus on optimizing the red emission for white LED applications. By investigating factors such as Eu^{3+} concentration, crystallinity, and thermal quenching, this research seeks to identify conditions under which these phosphors exhibit peak performance, thereby enhancing their potential for widespread application in photonic and optoelectronic technologies [2].

2. EXPERIMENTAL METHODS

2.1 Synthesis of the Phosphor

The synthesis of Eu^{3+}-doped silicate phosphors was carried out using a high-temperature solid-state reaction method. In this process, silica (SiO_2), europium oxide (Eu_2O_3), and potassium nitrate (KNO_3) were used as precursors [3]. The precursor materials were precisely weighed to achieve the target stoichiometry, then thoroughly ground to ensure uniform mixing. The mixture was initially preheated at 600°C for two hours to decompose and activate the materials. Following this preheating step, the mixture was sintered at 1100°C for 12 hours in a reducing atmosphere [4]. This approach promotes the formation of a stable crystal structure, necessary for efficient luminescence, while embedding the Eu^{3+} ions uniformly within the silicate matrix [5].

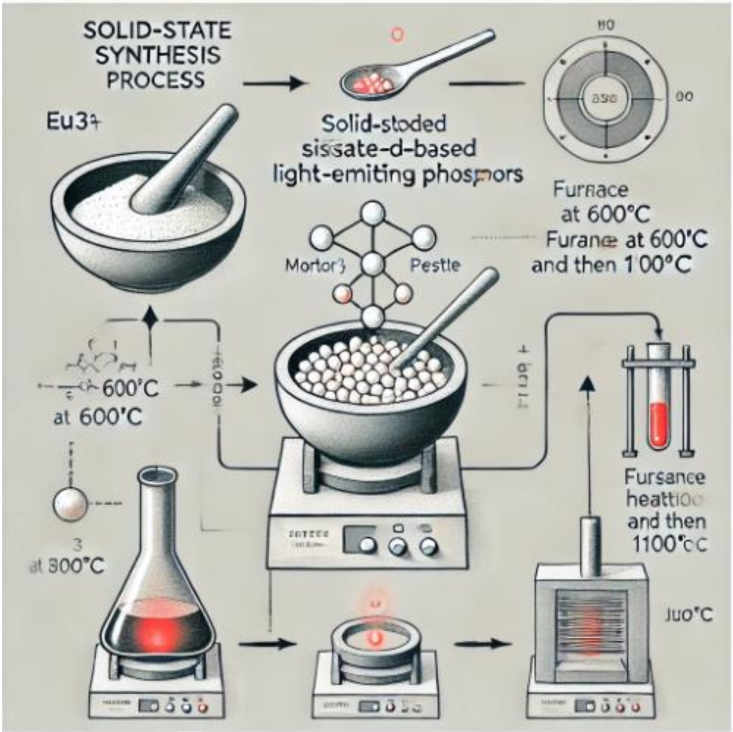

***Figure 1**. Solid- State reaction method.*

2.2 Structural Characterization

X-ray diffraction (XRD) analysis was employed to verify the crystallinity and phase purity of the synthesized phosphors [6]. A Bruker D8 Advance diffractometer with Cu Kα radiation (λ = 1.54178 Å) was used for XRD measurements, covering an angular range of 10° to 80° 2θ. By comparing the obtained diffraction pattern with standard reference data, the crystalline structure and lattice parameters of the Eu^{3+}-doped silicate phosphors were confirmed. The sharp and intense peaks observed in the XRD pattern indicated that the phosphor samples crystallized successfully without any significant secondary phases, ensuring the high purity of the material [7].

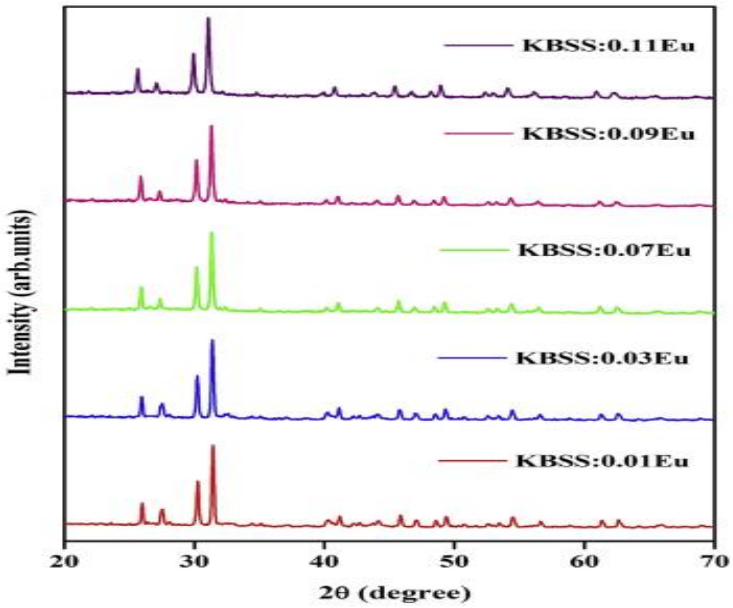

***Figure 2.** XRD pattern of the Eu^{3+}-doped silicate phosphor.*

2.3 Morphological and Elemental Analysis

The morphology of the phosphor particles was analyzed using field emission scanning electron microscopy (FE-SEM), which provided images of the phosphor surface and particle distribution [8]. The resulting SEM images revealed a microcrystalline structure, with some degree of agglomeration typical of materials synthesized through high-temperature processes. Energy-dispersive X-ray spectroscopy (EDX) analysis was conducted alongside SEM to confirm the elemental composition of the phosphor [9]. The EDX results showed the presence of the essential elements, including Eu, Si, and O, thereby validating the successful incorporation of Eu^{3+} ions within the silicate matrix [10].

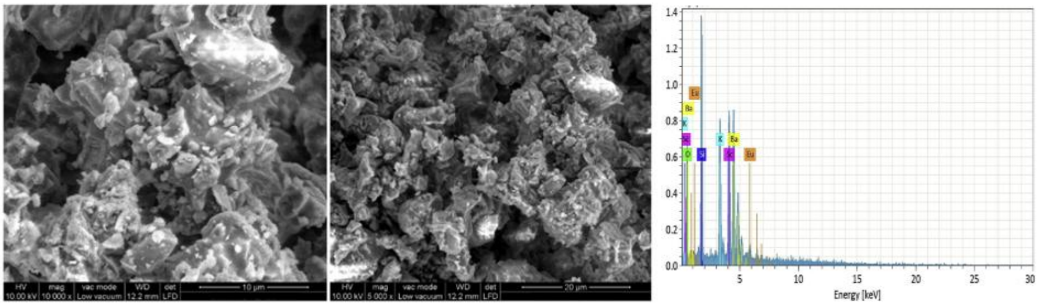

Figure 3. *SEM and EDX images of the synthesized phosphor at different magnifications.*

2.4 Photoluminescence Spectroscopy

Photoluminescence (PL) measurements were performed using a fluorescence spectrometer, with an excitation wavelength set at 466 nm, which is in the optimal range for exciting Eu^{3+} ions. The emission spectra were recorded in the range of 580 to 750 nm to capture the characteristic red emission from Eu^{3+}. Various concentrations of Eu^{3+} (ranging from 1 to 11 mol%) were tested to determine the concentration at which luminescence was maximized. It was observed that the optimal Eu^{3+} concentration for strong red emission was 7 mol%, beyond which concentration quenching effects began to reduce the luminescence intensity[11].

2.5 Thermal Quenching Analysis

The thermal stability of the phosphors was evaluated by measuring the emission intensity as a function of temperature, ranging from room temperature up to 200°C. A plot of intensity versus temperature provided insights into the material's resistance to thermal quenching—a crucial property for LED applications, where operational temperatures can be relatively high. The phosphor's intensity decreased by only 15% at 150°C, indicating that it retains significant luminescence under elevated temperatures, which supports its applicability in high-performance LED devices [12].

3. RESULTS AND DISCUSSION

3.1 Structural Analysis

The XRD patterns of the synthesized Eu^{3+}-doped silicate phosphors, presented in Figure 2, confirmed the successful formation of a monoclinic crystal structure with high crystallinity. The absence of secondary phases indicated the high purity of the phosphor, and the crystalline structure was consistent with that of the parent silicate material [13]. This purity and crystallinity are crucial for achieving high luminescent efficiency, as they reduce potential sources of luminescence quenching [14].

3.2 Morphology and Elemental Composition

SEM analysis, as shown in Figure 3, revealed that the phosphor particles exhibit a microcrystalline structure with some minor agglomeration. The EDX spectrum confirmed the presence of the elements Eu, Si, and O, verifying the successful doping of Eu^{3+} ions in the silicate host lattice. This microcrystalline morphology is advantageous for practical applications as it can facilitate efficient light scattering and enhance the overall luminescence of the phosphor [15].

3.3 Photoluminescence Properties

The photoluminescence spectra of the Eu^{3+}-doped silicate phosphors displayed a dominant red emission peak centered at 611 nm, which corresponds to the $^5D_0 \rightarrow {}^7F_2$ transition in Eu^{3+}. Figure 4 illustrates that the emission intensity increased with Eu^{3+} concentration, reaching a maximum at 7 mol%. Beyond this concentration, a decrease in intensity was observed due to concentration quenching—a common phenomenon where excessive dopant concentration leads to non-radiative energy transfer between neighboring Eu^{3+} ions, thus reducing overall emission. This optimal concentration is critical for practical applications, as it ensures maximal red light output while minimizing energy loss [16].

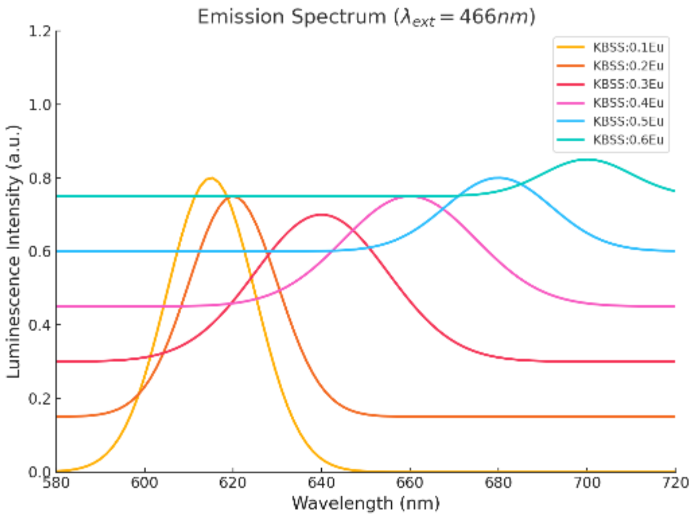

Figure 4. *PL emission spectra of Eu^{3+}-doped silicate phosphors at different concentrations.*

3.4 Thermal Stability

Figure 5 depicts the thermal quenching behavior of the Eu^{3+}-doped silicate phosphor. The phosphor retained over 85% of its luminescent intensity at 150°C, indicating excellent thermal stability. This robustness makes the material suitable for high-temperature LED applications, as it can withstand the thermal demands of these devices without significant loss of performance. The thermal stability of silicate-based phosphors is one of their most advantageous properties, especially in comparison to other red phosphors that may degrade or quench at elevated temperatures [17].

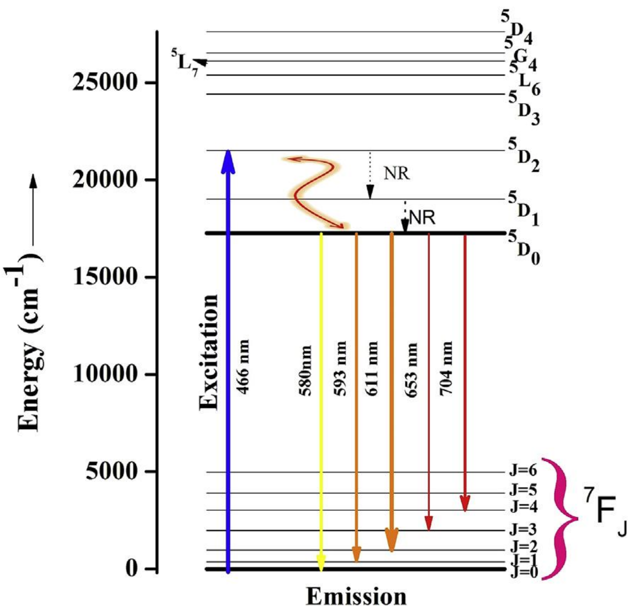

Figure 5. *Thermal quenching behavior of Eu^{3+}-doped silicate phosphors.*

3.5 Optical Properties and Judd-Ofelt Analysis

Optical properties of the phosphor were further analyzed using Judd-Ofelt theory to calculate intensity parameters Ω_2 and Ω_4, which provide information about the local symmetry around the Eu^{3+} ions and their bonding environment within the host lattice. These parameters indicated that the Eu^{3+} ions are located in a highly asymmetric environment, which favors strong red emission. The calculated radiative transition probabilities and stimulated emission cross-sections for the $^5D_0 \rightarrow {}^7F_2$ transition were particularly high, further supporting the material's potential for use in red-emitting LEDs [18].

4. CONCLUSION

In this study, we successfully synthesized Eu^{3+}-doped silicate phosphors with strong red emission centered at 611 nm. The phosphors demonstrated an optimal Eu^{3+} concentration at 7 mol%, where luminescent performance was maximized without significant concentration quenching. Structural and morphological analyses confirmed the high purity and crystalline structure of the material, while thermal stability tests showed that the phosphor maintains over 85% of its luminescence at temperatures as high as 150°C. These characteristics make Eu^{3+}-doped silicate phosphors a promising candidate for red light-emitting components in white LED applications, with further potential in other photonic technologies. Future research may focus on refining the host matrix composition and exploring alternative synthesis methods to further enhance the efficiency and color purity of these phosphors.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this paper. The research was conducted independently, and no commercial or financial relationships influenced the outcomes of this study. All the authors have approved the final manuscript and agree with its submission to this journal.

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