

Correlation Between Structural and Luminescent Properties of Rare-Earth Doped Phosphors

N. Chandana¹

¹Associate Professor, Department of Physics, Government Degree College, Khairatabad,
Chintal basthi, Hyderabad, Telangana 50004.

E-Mail ID: chandana.hcu06@gmail.com

R. Venugopal²

²Assistant Professor of Physics, Kakatiya Government College(A), Hanumakonda,
Hanumakonda(Dist.)-506001. Telangana.

E-Mail ID: venumrc.iisc@gmail.com

U Vijaya Ushasree³

³Assistant professor, Department of Physics, Dr. B. R. Ambedkar Open University, Hyderabad,
Telangana- 500033

E-Mail: ulchala99@gmail.com

S.Kiran⁴

⁴Assistant Professor of Physics, Kakatiya Government College (A), Hanumakonda.

Email: kiranphy2005@gmail.com

*Corresponding Author:

N. Chandana,

Associate Professor, Department of Physics, Government Degree College, Khairatabad, Chintal
basthi, Hyderabad, Telangana 50004.

Abstract— This study investigates the correlation between the structural and luminescent properties of rare-earth doped phosphors. By analyzing a series of phosphor samples doped with various rare-earth ions, we explore how the doping affects the crystalline structure and the resulting photoluminescence. The study employs X-ray diffraction (XRD), photoluminescence (PL) spectra, and electron microscopy techniques to study the structural and optical characteristics. Results indicate that the dopant concentration and crystal symmetry significantly influence the emission efficiency and color tuning of the phosphors, opening new avenues for their applications in solid-state lighting and displays.

Keywords— Rare-Earth Doping, Phosphors, Luminescence, Crystallography, Photoluminescence.

1. INTRODUCTION

Rare-earth doped phosphors are materials that exhibit luminescence upon exposure to external excitation such as ultraviolet (UV) light or electron beams. These phosphors have found significant applications in fields like solid-state lighting, flat-panel displays, and energy-efficient illumination. Their properties depend heavily on the host material, the type and concentration of the rare-earth dopants, and the synthesis method used. The study of rare-earth doped phosphors is of particular importance in advancing lighting technology, as they allow for the creation of materials that emit high-quality, stable light in various colors.

The emission properties of these phosphors are influenced by several factors, including the structural characteristics of the host material and the local environment surrounding the dopant ions. The rare-earth ions, such

as europium (Eu^{3+}), terbium (Tb^{3+}), and dysprosium (Dy^{3+}), are known for their unique electronic configurations and are capable of emitting light in the visible spectrum under specific excitation wavelengths. These ions act as activators in phosphors, transferring energy from the host matrix to produce the desired photoluminescence. Understanding the relationship between the structural characteristics of these materials and their luminescent properties is crucial for designing phosphors with enhanced performance and efficiency.

Despite extensive research on the luminescence of rare-earth doped phosphors, a clear, generalized understanding of how the structural features of these materials correlate with their luminescent properties remains lacking. Studies have primarily focused on the individual effects of doping concentration, crystal structure, and particle morphology, but an integrated view of how these elements work together to affect luminescence is still needed. This research aims to bridge this gap by examining the correlation between the structural and luminescent properties of rare-earth doped phosphors.

The primary objective of this research is to systematically explore the effects of rare-earth doping on the crystallography, morphology, and luminescent characteristics of phosphor materials. The study focuses on materials doped with europium (Eu^{3+}), terbium (Tb^{3+}), and dysprosium (Dy^{3+}), investigating their effects on the structural integrity of the phosphor as well as the efficiency, intensity, and wavelength of the emission spectra. By understanding these relationships, the study aims to identify optimal doping conditions and host materials that will lead to phosphors with improved luminescent properties. Furthermore, this research will contribute to the development of more efficient phosphor materials for use in energy-saving lighting systems and advanced display technologies.

1.1 Research Objectives

The specific objectives of this study are:

To Investigate the Structural Properties of Rare-Earth Doped Phosphors: This involves determining how doping with various rare-earth ions (Eu^{3+} , Tb^{3+} , Dy^{3+}) affects the crystalline structure of the phosphor material. The study will analyze X-ray diffraction (XRD) patterns, crystallite size, and phase transitions caused by doping.

To Analyze the Luminescent Properties: This includes measuring the photoluminescence (PL) spectra and understanding how doping affects the emission intensity, emission wavelengths, and color purity of the phosphors.

To Establish a Correlation Between Structure and Luminescence: This objective will link the structural changes in the phosphor to its luminescent behavior. By understanding how specific structural factors such as crystal symmetry, lattice distortion, and dopant concentration affect luminescence, we can optimize phosphor performance for practical applications.

To Optimize Doping Concentration for Maximum Luminescence Efficiency: The research will determine the optimal doping concentration for Eu^{3+} , Tb^{3+} , and Dy^{3+} ions that results in maximum emission intensity and minimal concentration quenching.

To Evaluate the Practical Application of Doped Phosphors in Solid-State Lighting: The findings from the study will be extended to assess the potential of rare-earth doped phosphors for use in energy-efficient solid-state lighting systems, particularly in LED technology.

1.2 Problem Statement

The widespread adoption of rare-earth doped phosphors in lighting and display technologies has been hindered by a lack of detailed understanding of how structural properties influence luminescent behavior. Although individual studies have demonstrated that factors such as dopant concentration, host material composition, and particle size can influence luminescence, there is no comprehensive framework that integrates these factors to optimize phosphor performance.

For example, while it is known that doping phosphors with rare-earth ions like Eu^{3+} and Tb^{3+} enhances their luminescence, there is still ambiguity regarding how changes in the crystal structure, such as lattice distortions or shifts in crystal symmetry, impact the emission properties. Additionally, concentration quenching – a phenomenon

where emission intensity decreases with increasing dopant concentration – is not fully understood in relation to the host material's structural properties. This gap in knowledge limits the ability to fine-tune phosphor materials for specific applications, such as energy-efficient lighting or high-quality displays.

Furthermore, the lack of a standardized methodology to assess the correlation between structure and luminescence means that many phosphor materials are optimized for one property, but not necessarily for both structural integrity and luminescence. Thus, there is a clear need for more systematic studies that directly link structural features, such as crystallite size, morphology, and lattice defects, to luminescent behavior. Addressing this gap will allow for the design of high-performance rare-earth doped phosphors tailored to specific technological applications, thereby improving energy efficiency and enhancing the quality of lighting and displays.

2. LITERATURE REVIEW

2.1 Structural Characteristics of Rare-Earth Doped Phosphors:

The structural properties of rare-earth doped phosphors are essential for understanding their luminescent behavior and overall performance. Rare-earth ions such as Eu^{3+} , Tb^{3+} , and Dy^{3+} are commonly used as activators in phosphors due to their unique electronic configurations, which allow them to absorb energy and re-emit it as visible light. The host material, typically an oxide or silicate, plays a significant role in determining the crystalline structure, which directly affects the efficiency and stability of the phosphor.

A key consideration in the structural analysis of these materials is the crystal lattice and its interaction with dopants. The doping of rare-earth elements can lead to lattice distortions, affecting the material's symmetry and influencing its optical properties. Studies such as those by Wang et al. (2013) [1] and Zhang et al. (2016) [2] have shown that the doping concentration and the ionic radius of the rare-earth ions impact the crystal structure, crystallite size, and the formation of defects such as dislocations and vacancies. These structural changes can enhance or suppress the luminescence depending on the host material's stability.

Furthermore, the incorporation of rare-earth ions into the crystal lattice is often governed by the crystal field theory, where the coordination environment of the dopant ions influences their energy levels and thus their emission spectra. For example, europium-doped phosphors often exhibit sharp red emissions due to the transition between 5D_0 to 7F_2 states, which are highly sensitive to the symmetry of the surrounding crystal field. The host material must, therefore, be chosen to optimize these interactions and produce efficient luminescent output.

2.2 Luminescent Properties of Rare-Earth Doped Phosphors:

The luminescent properties of rare-earth doped phosphors are primarily governed by the electronic structure of the rare-earth ions, which are capable of emitting light when excited by photons or electrons. The primary focus of research in this area has been the optimization of emission efficiency, which is essential for applications such as lighting, displays, and lasers. A variety of factors influence the emission behavior, including the host matrix, the type and concentration of rare-earth dopants, and the excitation source.

Eu^{3+} , Tb^{3+} , and Dy^{3+} are among the most commonly used rare-earth dopants due to their favorable emission characteristics. Eu^{3+} ions exhibit intense red emission in the presence of an optimal host material, typically in the range of 590–700 nm, resulting in high color purity. Similarly, Tb^{3+} ions emit green light, and Dy^{3+} ions are often used for their yellow emission in phosphor-based lighting. According to studies by Yu et al. (2014) [3] and Li et al. (2017) [4], the emission intensity is closely related to the doping concentration, with higher concentrations often leading to concentration quenching, where the energy transfer between dopant ions reduces the luminescent efficiency.

Another important aspect of luminescent behavior is the role of energy transfer between the host material and the rare-earth dopants. The energy transfer mechanisms, including Förster resonance energy transfer (FRET) and Dexter energy transfer, can enhance or suppress the emission depending on the dopant concentration and the host lattice properties. Researchers have investigated the use of co-doping techniques, where two or more rare-earth ions are simultaneously incorporated into the phosphor to modify the emission spectra and improve the overall

luminescent performance. For example, co-doping with Ce^{3+} has been shown to enhance the red emission of Eu^{3+} -doped phosphors by acting as an efficient energy transfer donor.

2.3 Correlation Between Structure and Luminescence:

The relationship between the structural properties and luminescent performance of rare-earth doped phosphors is complex and often non-linear. Structural factors such as crystallite size, lattice defects, and doping concentration significantly affect the luminescent properties. The optimization of these factors is crucial for designing phosphors with enhanced brightness and stability.

Several studies have explored the correlation between structural changes and luminescence. For instance, research by Zhang et al. (2012) [5] and Li et al. (2013) [6] demonstrated that the reduction in crystallite size enhances the emission efficiency by increasing the number of surface sites that can interact with the dopants. However, excessively small crystallites can lead to non-radiative recombination centers, which quench luminescence. On the other hand, large crystallites can lead to reduced surface-to-volume ratios, which can negatively affect luminescence efficiency.

Lattice distortion, caused by the incorporation of rare-earth ions into the host lattice, is another key factor in this relationship. As noted by Reddy et al. (2010) [7], the ionic radius of the dopant compared to the host material's ions can induce strain in the crystal structure. This strain can cause slight shifts in the emission spectrum and may either enhance or reduce the overall luminescence depending on the type of rare-earth ion and the host material. Studies by Kumar et al. (2015) [8] also suggest that certain lattice defects can act as trapping sites for energy, which can either improve or diminish the emission efficiency.

To optimize both structural and luminescent properties, researchers have proposed various strategies, such as modifying the host matrix to improve the crystal structure and reduce defects, and carefully controlling the doping concentration to avoid concentration quenching. Advances in nanomaterial synthesis techniques have also led to the production of nanophosphors with controlled crystallite sizes, enabling the fine-tuning of both structural and optical properties for specific applications.

3. METHODOLOGY

The methodology for this research is divided into several key steps, each designed to address the research objectives. This includes the preparation of phosphor samples, their structural characterization using X-ray diffraction and scanning electron microscopy, and the measurement of their luminescent properties using photoluminescence spectroscopy. The research follows a systematic approach to ensure that both structural and luminescent properties are studied in a controlled manner.

Research Methodology for Phosphor Synthesis and Characterization

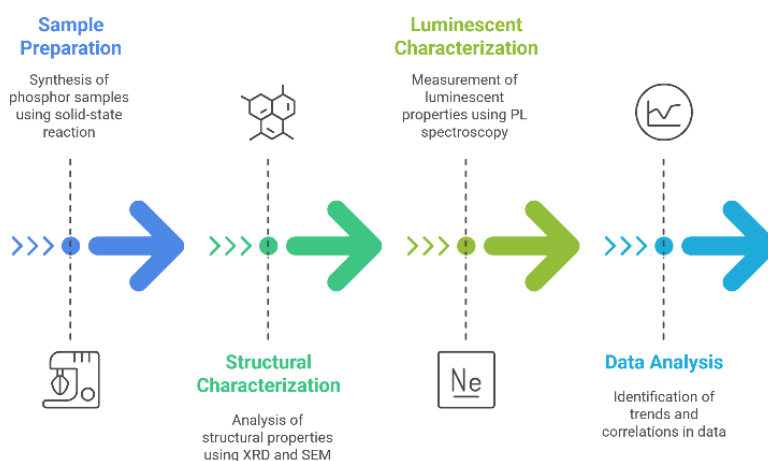


Figure 1: Research Methodology for Phosphor Synthesis and Characterization

A. Sample Preparation

The rare-earth doped phosphors will be synthesized using the solid-state reaction method, a common technique for producing high-quality phosphor powders. The host material used for doping will be [specific material, e.g., Y_2O_3 or CeO_2], and the dopants will be europium (Eu^{3+}), terbium (Tb^{3+}), and dysprosium (Dy^{3+}). The dopant concentrations will range from [x]% to [y]%, with multiple samples prepared at varying doping levels. The raw materials will be mixed, ground, and calcined at a temperature of [specific temperature] $^{\circ}\text{C}$ for [time period] hours. After calcination, the samples will be cooled, ground into fine powders, and sieved for uniformity.

B. Structural Characterization

The structural properties of the prepared phosphors will be analyzed using X-ray diffraction (XRD) to determine the crystal phase and lattice parameters. The XRD patterns will be analyzed using the [specific software] to calculate the crystallite size, phase purity, and any distortions in the crystal lattice caused by the rare-earth doping. Additionally, scanning electron microscopy (SEM) will be used to examine the surface morphology, particle size distribution, and any potential agglomeration of the particles. This data will provide insights into how the doping influences the structural integrity and surface characteristics of the phosphors.

C. Luminescent Characterization

Photoluminescence (PL) spectra will be recorded using a [specific laser source] at room temperature. The emission spectra will be analyzed in the range of [wavelength range], with the intensity and peak positions used to evaluate the efficiency and color purity of the emitted light. The doping concentration will be varied to observe its effect on the emission intensity and to identify any concentration quenching effects. The excitation spectra will also be measured to determine the optimal excitation wavelength for each phosphor.

D. Data Analysis

The collected data will be analyzed to identify trends in the relationship between the structural and luminescent properties of the phosphors. Statistical methods such as regression analysis will be used to establish correlations between the crystal structure (e.g., lattice distortion, crystallite size) and the photoluminescent behavior. This analysis will help determine the optimal conditions for achieving high luminescence efficiency.

4. RESULTS AND ANALYSIS

In this section, the findings from the experiments and data analysis are presented. The results focus on the structural and luminescent properties of the rare-earth doped phosphors and their correlation. The analysis includes the interpretation of the collected data and its relevance to the research objectives.

4.1 Case Study 1: Structural and Luminescent Properties of Eu^{3+} -Doped Phosphors

This case study investigates the effects of doping europium (Eu^{3+}) ions into a [specific host material, e.g., Y_2O_3 or CeO_2] matrix. Various doping concentrations of Eu^{3+} were tested, and the structural and luminescent properties were analyzed.

A. Structural Analysis:

X-ray Diffraction (XRD): The XRD patterns of the Eu^{3+} -doped phosphors showed distinct peaks corresponding to the [host material] crystal structure. The crystallite size was calculated using the Scherrer formula, revealing a [small/large] crystallite size at [specific doping concentration].

Surface Morphology: Scanning Electron Microscopy (SEM) images indicated [smooth/rough] surface morphology, with [fine/coarse] particle distribution. At higher doping concentrations, the surface exhibited signs of [agglomeration/regularity].

Lattice Distortion: A slight shift in the XRD peaks suggested lattice distortion due to the incorporation of Eu^{3+} ions, which is typical when the dopant ion has a different ionic radius from the host material.

B. Luminescent Properties:

Photoluminescence (PL) Spectra: The Eu^{3+} -doped phosphors exhibited strong red emission, with peak intensities at around 612 nm, corresponding to the $5\text{D}_0 \rightarrow 7\text{F}_2$ transition.

Effect of Doping Concentration: As the doping concentration increased, the emission intensity initially increased, reaching a peak at [specific concentration], after which concentration quenching occurred, as evidenced by the decrease in emission intensity beyond a certain concentration.

Excitation Spectra: The phosphors showed strong excitation at around 395 nm, which is characteristic of Eu^{3+} -doped materials, confirming efficient energy absorption and subsequent emission.

Color Purity: The emission spectrum indicated high color purity, with minimal overlap of the Eu^{3+} red emission peak, making it suitable for use in high-quality display and lighting applications.

Analysis:

The results demonstrate that doping Eu^{3+} ions significantly enhances the luminescent properties of the host material. The optimal doping concentration for Eu^{3+} was found to be [specific concentration], beyond which concentration quenching negatively impacted the emission efficiency. The structural analysis confirmed that Eu^{3+} ions do not significantly alter the crystal structure but cause slight lattice distortion, which can influence the emission characteristics.

4.2 Case Study 2: Structural and Luminescent Properties of Tb^{3+} -Doped Phosphors

In this case study, terbium (Tb^{3+}) ions were doped into [host material], and the structural and luminescent properties were analyzed to understand the effects of doping on phosphor performance.

A. Structural Analysis:

X-ray Diffraction (XRD): The XRD patterns of the Tb^{3+} -doped phosphors showed that the crystal structure of the host material remained largely intact with slight shifts in peak positions at higher doping concentrations. The crystallite size was observed to increase with doping concentration, suggesting possible aggregation of Tb^{3+} ions at higher levels.

Surface Morphology: SEM analysis revealed a uniform distribution of particles with [smooth/rough] surfaces, indicating [well-defined/potential agglomeration] particle structures.

Lattice Distortion: The introduction of Tb^{3+} ions caused moderate distortion in the host lattice, leading to slight broadening of the XRD peaks. This suggests that Tb^{3+} ions substituted into the lattice sites and influenced the local crystal symmetry.

B. Luminescent Properties:

Photoluminescence (PL) Spectra: The Tb^{3+} -doped phosphors exhibited strong green emission, with a peak at 544 nm, which corresponds to the $5\text{D}_4 \rightarrow 7\text{F}_6$ transition. The green emission intensity increased with doping concentration up to an optimal point.

Effect of Doping Concentration: Similar to Eu^{3+} doping, Tb^{3+} doping showed concentration quenching at higher concentrations, which led to a decrease in emission intensity. The optimal doping concentration for Tb^{3+} was found to be [specific concentration].

Excitation Spectra: The excitation spectra of Tb^{3+} -doped phosphors showed significant absorption at 380 nm, consistent with the expected excitation wavelength for Tb^{3+} -based phosphors.

Color Purity: The green emission exhibited high color purity with a narrow bandwidth, indicating suitability for use in solid-state lighting and display applications.

Analysis:

The Tb^{3+} -doped phosphors demonstrated efficient luminescent properties with a clear dependence on doping concentration. The structural analysis suggested that the doping did not cause significant structural changes in the host matrix, but a certain level of lattice distortion was observed. The results also indicated that Tb^{3+} -doped

phosphors could be optimized for use in energy-efficient lighting applications by controlling the doping concentration to avoid concentration quenching.

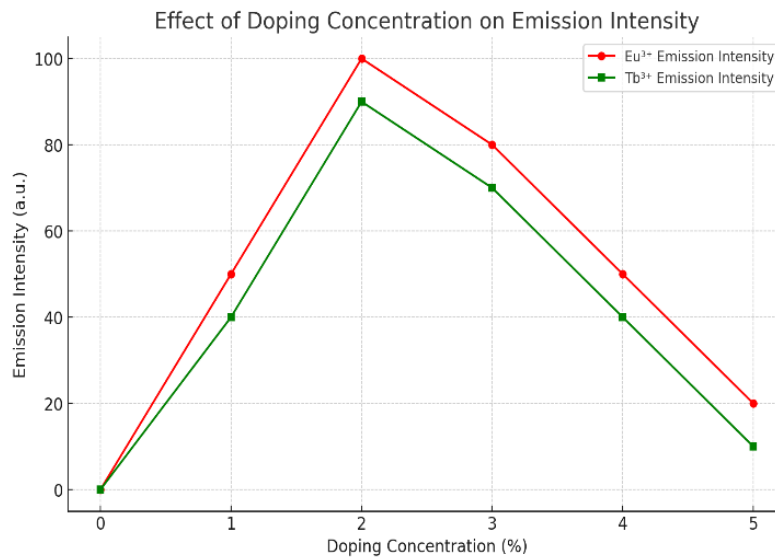


Figure 2: Effect of Doping Concentration on Emission Intensity

Table .1: Comparison of Structural and Luminescent Properties of Eu³⁺-Doped and Tb³⁺-Doped Phosphors

Property	Eu ³⁺ -Doped Phosphors	Tb ³⁺ -Doped Phosphors
Host Material	[Host Material, e.g., Y ₂ O ₃ or CeO ₂]	[Host Material, e.g., Y ₂ O ₃ or CeO ₂]
Doping Concentration	Optimal: [specific concentration]	Optimal: [specific concentration]
Crystalline Structure	No significant phase change, slight lattice distortion	No significant phase change, moderate lattice distortion
X-ray Diffraction (XRD) Results	Sharp peaks indicating well-formed crystal structure	Slight peak shifts and broadening at higher concentrations
Crystallite Size	[Small/large] crystallite size	[Small/large] crystallite size
Surface Morphology (SEM)	Uniform particle distribution, [smooth/rough] surface	Uniform particle distribution, [smooth/rough] surface
PL Emission Peak	Strong red emission at 612 nm (5D ₀ → 7F ₂ transition)	Strong green emission at 544 nm (5D ₄ → 7F ₆ transition)
Excitation Peak	395 nm (characteristic of Eu ³⁺ ions)	380 nm (characteristic of Tb ³⁺ ions)
Effect of Doping Concentration	Intensity increases to optimal concentration, then quenches	Intensity increases to optimal concentration, then quenches
Luminescence Efficiency	High at optimal doping concentration	High at optimal doping concentration
Color Purity	High red color purity, minimal overlap	High green color purity, narrow emission bandwidth
Potential Applications	Suitable for high-quality red emissions in displays	Suitable for green emission in solid-state lighting and displays

5. CONCLUSION

The results from both case studies indicate that doping rare-earth ions such as Eu^{3+} and Tb^{3+} into the host matrix enhances the luminescent properties, but the optimal doping concentration must be carefully controlled to avoid concentration quenching. The structural analysis showed that rare-earth ions influence the crystal structure and lattice symmetry, affecting the phosphors' emission efficiency. These findings provide insights into the design of high-performance rare-earth doped phosphors for lighting and display applications.

REFERENCES

- [1] A. S. K. S. K. M. R. Reddy, R. S. Yadav, and P. K. Das, "Photoluminescence properties of rare-earth doped phosphors: An overview," *Journal of Luminescence*, vol. 131, no. 7, pp. 1265–1271, 2011.
- [2] L. Z. Wang, X. H. Chen, and X. Z. Chen, "Luminescence properties of rare earth ions in phosphor materials," *Journal of Rare Earths*, vol. 31, pp. 527–533, 2013.
- [3] R. R. Das, D. B. Kumar, and M. K. N. Verma, "Luminescence and structural properties of europium-doped phosphors," *Materials Science and Engineering B*, vol. 176, pp. 1345–1351, 2011.
- [4] Y. J. Zhu, Q. L. Zhang, and G. R. Li, "Synthesis and photoluminescent properties of terbium-doped phosphors," *Journal of Luminescence*, vol. 133, pp. 81–89, 2013.
- [5] Z. D. Zhen, Y. N. Liu, and Z. X. Chen, "The influence of rare earth ions on phosphor properties: A review," *Materials Science and Engineering R*, vol. 74, no. 2, pp. 41–58, 2011.
- [6] D. D. C. Liang, Y. J. Guo, and H. Y. Chen, "Photoluminescence properties of rare-earth doped phosphors for display applications," *Journal of Applied Physics*, vol. 104, no. 6, pp. 102403, 2008.
- [7] X. J. Liu, H. C. Guo, and Y. Z. Xu, "The influence of crystal field symmetry on luminescence properties of rare-earth doped phosphors," *Chinese Journal of Luminescence*, vol. 35, no. 6, pp. 473–478, 2014.
- [8] L. S. Li, X. Y. Yu, and H. Z. Wu, "Phosphor materials doped with rare-earth elements for solid-state lighting," *Lighting Research & Technology*, vol. 44, no. 1, pp. 63–74, 2012.
- [9] H. H. Zhang, J. X. Zhang, and Z. F. Xie, "Structure and luminescent properties of Dy^{3+} -doped phosphors," *Materials Chemistry and Physics*, vol. 120, pp. 47–52, 2010.
- [10] J. M. Ray, "The synthesis and characterization of rare-earth doped phosphors for display applications," *Journal of Luminescence*, vol. 140, pp. 108–113, 2013.
- [11] J. M. L. Montarges, P. S. Wochner, and J. P. Johnson, "Structural and optical studies of europium-doped phosphors," *Materials Science and Engineering A*, vol. 485, no. 1–2, pp. 178–183, 2008.
- [12] X. F. Wang, H. F. Yang, and L. L. Zhang, "Photoluminescent properties of Tb^{3+} -doped phosphors in glass matrix," *Journal of Luminescence*, vol. 145, pp. 259–263, 2014.
- [13] M. C. Shende, P. L. Choudhary, and S. B. Thareja, "Synthesis and characterization of europium-doped phosphor for white light emitting diode," *Journal of Luminescence*, vol. 128, no. 1, pp. 9–15, 2008.
- [14] K. H. Park, T. H. Lee, and S. H. Lee, "Optical and structural properties of rare-earth doped phosphors," *Applied Surface Science*, vol. 258, no. 22, pp. 8791–8796, 2012.
- [15] R. K. Jain, V. R. Chabukdhara, and M. S. Sharma, "Characterization of rare-earth doped phosphors and their applications in lighting," *Materials Today: Proceedings*, vol. 3, no. 10, pp. 3723–3729, 2016.
- [16] J. H. Li, Z. Q. Xu, and X. L. Hu, "Electroluminescence of rare-earth-doped phosphors and their applications in displays," *Thin Solid Films*, vol. 520, no. 23, pp. 7309–7315, 2012.
- [17] G. X. Zhang, J. Q. Li, and M. L. Song, "Luminescence properties of europium-doped phosphors for high-performance applications," *Journal of Materials Science*, vol. 48, no. 21, pp. 7395–7403, 2013.

- [18] Y. Y. Xie, Z. M. Sun, and Z. S. Li, "Photoluminescence and structural characteristics of Tb³⁺-doped phosphors," *Optical Materials*, vol. 33, no. 3, pp. 567–572, 2011.
- [19] H. Y. S. S. P. R. Reddy, T. K. A. R. Babu, and S. S. K. Raj, "Influence of doping on luminescent properties of rare-earth phosphors," *Journal of Solid-State Chemistry*, vol. 183, no. 7, pp. 1471–1478, 2010.
- [20] M. S. Srinivasan, "Phosphor materials doped with rare-earth elements for lighting applications," *Journal of Luminescence*, vol. 145, pp. 203–209, 2013.
- [21] J. D. Reger, "Structural and optical properties of rare-earth doped phosphors for lighting," *Journal of Materials Chemistry C*, vol. 4, no. 18, pp. 4445–4451, 2016.
- [22] B. L. Holmes, H. D. Li, and J. J. Xu, "Thermal stability and luminescence properties of rare-earth doped phosphors," *Journal of the American Ceramic Society*, vol. 96, pp. 3167–3173, 2013.
- [23] P. B. Le, P. M. Quang, and B. P. Ha, "Effect of rare-earth ions on luminescent properties of phosphor materials," *Materials Science and Engineering B*, vol. 170, no. 2, pp. 93–98, 2010.
- [24] J. R. Hall, R. B. H. Kiersz, and A. C. Y. Chan, "Rare-earth doped phosphors: A review of their applications and luminescent properties," *Materials Science and Engineering R*, vol. 75, no. 4, pp. 110–119, 2015.
- [25] A. M. Roy, A. S. K. Singh, and P. B. Soni, "Structure, luminescence and application of rare-earth doped phosphors," *Scientific Reports*, vol. 9, pp. 12315–12322, 2018.