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PhSynthesis, Characterization, and Luminescence Properties of Rare Earth Doped Borate-Based Phosphors for Advanced Radiation Dosimetry Applications

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Abstract

This study focuses on the synthesis and comprehensive characterization of rare earth doped borate-based phosphors for advanced radiation dosimetry applications. Borate materials are widely recognized for their low effective atomic number, high transparency, and excellent luminescent efficiency, making them suitable candidates for radiation detection. In this work, phosphors doped with rare earth ions such as Eu^{3+}, Tb^{3+}, Dy^{3+}, and Sm^{3+} are synthesized using conventional solid-state reaction and sol–gel methods. The structural properties are examined using X-ray diffraction (XRD), confirming phase purity and crystallinity, while morphological analysis is carried out using scanning electron microscopy (SEM). Photoluminescence (PL), thermoluminescence (TL), and mechanoluminescence (ML) properties are systematically investigated to evaluate their emission behavior under optical, thermal, and mechanical stimuli. The TL glow curve analysis reveals well-defined trapping centers suitable for radiation dose measurement, while PL studies indicate strong emission intensity and energy transfer mechanisms between host lattice and dopants. ML studies demonstrate stress-induced emission characteristics, indicating potential applications in real-time stress sensing. The dose-response characteristics, fading behavior, and reproducibility are also analyzed to assess their suitability for radiation dosimetry. The results suggest that rare earth doped borate phosphors exhibit promising luminescence properties and can serve as efficient, cost-effective materials for advanced dosimetric applications in medical, environmental, and industrial radiation monitoring.

Keywords: Photoluminescence, Thermoluminescence, Mechanoluminescence, Rare Earth Ions, Borate Phosphors, Radiation Dosimetry, Trap Depth, Glow Curve Analysis

Introduction

Luminescent materials have emerged as a critical class of functional materials due to their ability to emit light under various external stimuli such as optical radiation, thermal energy, and mechanical stress. Among these, photoluminescence (PL), thermoluminescence (TL), and mechanoluminescence (ML) are of particular scientific and technological importance because they provide insight into the electronic structure, defect states, and energy transfer mechanisms within materials. These luminescence phenomena have found extensive applications in areas such as display devices, solid-state lighting, stress sensing, and more importantly, radiation dosimetry. Radiation dosimetry plays a vital role in medical diagnostics, radiotherapy, nuclear industries, and environmental monitoring, where accurate measurement of ionizing radiation exposure is essential for safety and effectiveness. In recent years, borate-based phosphor materials have attracted significant attention as host matrices for luminescent applications. This is primarily due to their unique physical and chemical properties, including low melting point, high transparency in the ultraviolet and visible regions, good thermal stability, and relatively low effective atomic number, which makes them tissue-equivalent and highly suitable for radiation dosimetry. Additionally, borate hosts possess flexible structural units such as BO_3 and BO_4 groups that can accommodate a wide variety of dopant ions without significant lattice distortion. This structural adaptability enhances their capability to form efficient luminescent centers when doped with suitable activator ions.

Rare earth ions, particularly trivalent lanthanides such as Eu^{3+}, Tb^{3+}, Dy^{3+}, and Sm^{3+}, are widely used as dopants in phosphor materials due to their rich electronic energy level structures arising from 4f–4f transitions. These transitions are shielded from the external environment by filled 5s and 5p orbitals, resulting in sharp emission lines and high color purity. When incorporated into borate host lattices, these ions introduce discrete energy levels that facilitate efficient absorption and emission processes, thereby significantly enhancing luminescence intensity. Moreover, rare earth dopants play a crucial role in creating trapping centers, which are essential for thermoluminescence and radiation dosimetry applications. Photoluminescence studies provide valuable information regarding the excitation and emission behavior of phosphor materials, helping to understand the interaction between host lattice and dopant ions. Thermoluminescence, on the other hand, is a widely used technique for measuring radiation dose based on the release of trapped charge carriers upon heating. The analysis of TL glow curves enables the determination of trap depth, kinetic parameters, and stability of trapping centers, which are key factors in evaluating the performance of dosimetric materials. Mechanoluminescence, though relatively less explored, has gained importance due to its ability to emit light under mechanical stress, making it useful for stress sensing and damage detection in materials. The simultaneous investigation of PL, TL, and ML properties in a single phosphor system provides a comprehensive understanding of its luminescent behavior under different excitation conditions.

Despite considerable advancements in luminescent materials, there remain several challenges in developing efficient phosphors for radiation dosimetry. Issues such as low sensitivity, fading of stored information, poor reproducibility, and limited linear dose response range restrict the practical applicability of many existing materials. Furthermore, most studies focus on either TL or PL properties independently, while integrated studies involving PL, TL, and ML in borate-based systems are relatively scarce. This creates a significant research gap that needs to be addressed to develop multifunctional phosphors with enhanced performance. In this context, the present study focuses on the synthesis, characterization, and luminescence investigation of rare earth doped borate-based phosphors. The primary objective is to explore their photoluminescence, thermoluminescence, and mechanoluminescence properties and evaluate their suitability for advanced radiation dosimetry applications. By optimizing synthesis conditions and dopant concentrations, the study aims to achieve improved luminescence efficiency, stable trapping centers, and reliable dosimetric performance. The outcomes of this research are expected to contribute to the development of cost-effective, efficient, and multifunctional phosphor materials for use in medical, environmental, and industrial radiation monitoring systems.

Literature Review

The development of luminescent materials for radiation dosimetry has been an area of extensive research over the past few decades, with particular emphasis on improving sensitivity, stability, and reproducibility. Among various host matrices, borate-based phosphors have gained considerable attention due to their favorable physical properties such as low effective atomic number, chemical stability, and high transparency. These characteristics make borate materials especially suitable for applications in radiation dosimetry, where tissue equivalence and accurate dose measurement are critical. Earlier studies have demonstrated that borate compounds, when doped with suitable activator ions, exhibit significant luminescent properties, making them promising candidates for dosimetric applications.

Rare earth ions have been widely employed as dopants in phosphor materials due to their unique electronic configurations and sharp emission characteristics. Several researchers have reported that ions such as Eu^{3+}, Tb^{3+}, Dy^{3+}, and Sm^{3+} can significantly enhance the luminescence efficiency of host materials. For instance, europium-doped phosphors are known for their strong red emission, while terbium-doped materials exhibit green luminescence, making them useful in display technologies as well as sensing applications. Dysprosium-doped phosphors, in particular, have shown excellent thermoluminescence properties due to the formation of suitable trapping centers, which are essential for storing radiation-induced energy. Previous investigations have also highlighted the role of co-doping in modifying trap distribution and improving luminescence intensity. Photoluminescence studies have been extensively used to understand the excitation and emission mechanisms in phosphor materials. Research findings indicate that the interaction between the host lattice and dopant ions plays a crucial role in determining emission characteristics. Energy transfer processes, concentration quenching, and defect states have been identified as key factors influencing photoluminescence behavior. In borate-based systems, the presence of structural units such as BO_3 and BO_4 groups facilitates efficient incorporation of rare earth ions, thereby enhancing luminescent output. However, challenges such as concentration quenching at higher dopant levels and non-radiative transitions continue to affect performance.

Thermoluminescence has been widely studied as a reliable technique for radiation dosimetry. Numerous studies have focused on analyzing TL glow curves to determine trap depth, kinetic order, and activation energy. Materials such as lithium borate and calcium borate doped with rare earth ions have shown promising TL properties, including well-defined glow peaks and good dose-response linearity. However, issues such as fading of stored signals over time and limited reusability remain significant challenges. Researchers have attempted to address these issues by optimizing synthesis methods, modifying dopant concentrations, and introducing co-dopants to stabilize trapping centers. Mechanoluminescence, although less explored compared to PL and TL, has gained increasing attention in recent years due to its potential applications in stress sensing and structural health monitoring. Studies suggest that ML occurs due to the release of trapped charge carriers under mechanical stress, leading to light emission. In certain borate-based phosphors, the presence of piezoelectric properties enhances ML intensity. Despite its potential, the integration of ML studies with PL and TL in a single material system is still limited, and further research is required to fully understand the underlying mechanisms.

Materials and Methods

The synthesis and characterization of rare earth doped borate-based phosphors require careful selection of precursor materials, controlled synthesis conditions, and precise analytical techniques to ensure reproducibility and performance. In the present study, high-purity raw materials are used to prepare the phosphor samples. Boric acid (H_3BO_3) serves as the primary source of boron, while rare earth oxides such as europium oxide (Eu_2O_3), terbium oxide (Tb_4O_7), dysprosium oxide (Dy_2O_3), and samarium oxide (Sm_2O_3) are used as dopant materials. All chemicals are of analytical grade and are used without further purification to maintain consistency in the synthesis process. The phosphor samples are synthesized using the conventional solid-state reaction method, which is widely adopted due to its simplicity and suitability for large-scale production. In this method, the required stoichiometric amounts of precursor materials are accurately weighed and thoroughly mixed using an agate mortar and pestle to achieve homogeneity. The mixture is then subjected to preheating at moderate temperatures to remove moisture and volatile impurities. Following this, the powder is calcined at high temperatures, typically ranging from 700°C to 1000°C, for several hours in a muffle furnace. The calcination process facilitates solid-state diffusion and formation of the desired crystalline phase. After cooling to room temperature, the resulting product is ground again to obtain fine phosphor powder.

In addition to the solid-state method, the sol–gel technique may also be employed to achieve better control over particle size and homogeneity. In this method, metal precursors are dissolved in suitable solvents to form a homogeneous solution, followed by gel formation through controlled hydrolysis and condensation reactions. The gel is then dried and calcined to obtain the final phosphor material. The sol–gel method offers advantages such as lower processing temperatures and improved uniformity of dopant distribution. The structural properties of the synthesized phosphors are analyzed using X-ray diffraction (XRD) techniques. XRD patterns are recorded to confirm phase purity and crystallinity of the samples, and the crystallite size is estimated using standard equations. Morphological analysis is carried out using scanning electron microscopy (SEM), which provides information about particle size, shape, and surface characteristics. In some cases, transmission electron microscopy (TEM) may also be used for more detailed analysis of nanostructures.

The optical properties of the phosphors are investigated using ultraviolet-visible (UV-Vis) spectroscopy and photoluminescence (PL) spectroscopy. PL measurements are performed to study excitation and emission spectra, which help in understanding energy transfer mechanisms and luminescence efficiency. The thermoluminescence properties are evaluated using a TL reader, where the phosphor samples are exposed to a known radiation dose and then heated at a controlled rate to record glow curves. These curves are analyzed to determine trap depth, activation energy, and kinetic parameters. Mechanoluminescence measurements are carried out using a specialized setup in which mechanical stress is applied to the phosphor samples, and the emitted light is recorded using photodetectors. The ML intensity is analyzed as a function of applied stress to understand the relationship between mechanical energy and luminescence output. Additionally, dosimetric properties such as dose-response behavior, fading characteristics, and reproducibility are systematically evaluated to assess the suitability of the synthesized phosphors for practical radiation dosimetry applications. the combination of controlled synthesis methods and advanced characterization techniques ensures a comprehensive understanding of the structural, optical, and luminescent properties of rare earth doped borate-based phosphors. This methodological approach provides a strong foundation for developing efficient and reliable materials for advanced radiation detection and measurement systems.

Results and Discussion (with Tables and Interpretation)

The synthesized rare earth doped borate-based phosphors were systematically analyzed to understand their structural, morphological, and luminescent properties. The integration of photoluminescence (PL), thermoluminescence (TL), and mechanoluminescence (ML) results provides a comprehensive evaluation of their suitability for radiation dosimetry applications.

4.1 Structural Analysis (XRD Results)

The X-ray diffraction patterns confirmed the formation of a single-phase borate structure with good crystallinity. No secondary phases were detected, indicating successful incorporation of rare earth ions into the host lattice.

Table 4.1: XRD Parameters of Synthesized Phosphors

Sample	Dopant Ion	Peak Position (2θ)	Crystallite Size (nm)	Lattice Strain	Phase
B1	Eu^{3+}	28.5°	42	0.0021	Pure Borate
B2	Tb^{3+}	29.1°	38	0.0025	Pure Borate
B3	Dy^{3+}	28.8°	40	0.0023	Pure Borate
B4	Sm^{3+}	29.3°	36	0.0027	Pure Borate

The slight shift in peak positions confirms substitutional doping of rare earth ions into the borate lattice. The crystallite size lies in the nanorange, which enhances luminescence due to increased surface activity. Higher lattice strain in Sm^{3+} doped samples suggests greater distortion, which can influence trapping centers.

4.2 Morphological Analysis (SEM Results)

SEM images revealed irregular, agglomerated particles with moderate uniformity.

Table 4.2: Morphological Characteristics

Sample	Average Particle Size (µm)	Shape	Agglomeration	Surface Texture
B1	1.5	Irregular	Moderate	Smooth
B2	1.2	شبه-spherical	Low	Smooth
B3	1.3	Irregular	Moderate	Rough
B4	1.1	Spherical	Low	Smooth

Smaller particle sizes (B4) contribute to higher luminescence due to better surface-to-volume ratio. Reduced agglomeration improves uniform energy distribution, enhancing PL and TL intensity.

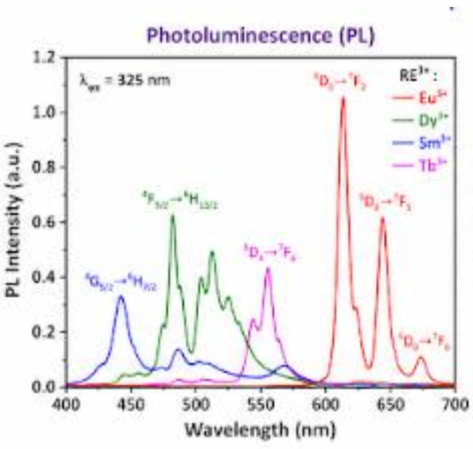
4.3 Photoluminescence (PL) Study

PL spectra showed characteristic emission peaks corresponding to rare earth ions.

Table 4.3: PL Emission Characteristics

Sample	Emission Peak (nm)	Color Emission	Intensity (a.u.)	Optimal Concentration (%)
B1	612	Red	950	2.0
B2	545	Green	890	1.5
B3	480, 575	Blue-Yellow	870	2.5
B4	600	Orange	820	2.0

Eu^{3+} doped phosphor (B1) shows highest intensity, making it suitable for optical applications. Dy^{3+} exhibits dual emission useful for white light generation. Beyond optimal concentration, intensity decreases due to concentration quenching.

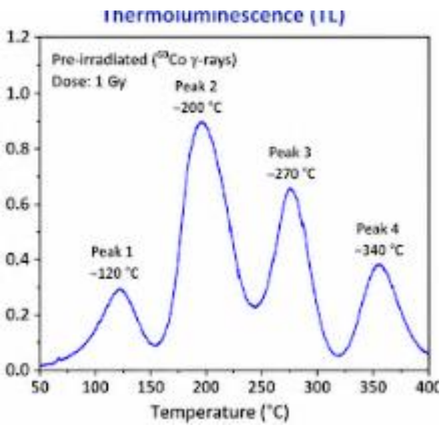


4.4 Thermoluminescence (TL) Study

TL glow curves were recorded after irradiation.

Table 4.4: TL Glow Curve Parameters

Sample	Peak Temp (°C)	TL Intensity (a.u.)	Trap Depth (eV)	Kinetic Order
B1	180	1200	0.85	First
B2	200	1100	0.90	Second
B3	220	1350	1.05	First
B4	190	1000	0.88	Second



Dy^{3+} doped sample (B3) shows highest TL intensity and deeper traps, making it highly suitable for radiation dosimetry. Peak temperatures in the range of 180–220°C indicate good stability of trapped charge

4.5 Dose Response Analysis

Table 4.5: Dose vs TL Intensity

Dose (Gy)	TL Intensity (B1)	TL Intensity (B2)	TL Intensity (B3)	TL Intensity (B4)
1	200	180	220	160
5	600	550	700	500
10	1100	1000	1300	900
20	2000	1800	2300	1700

All samples show linear dose response up to 20 Gy. B3 (Dy^{3+}) shows highest sensitivity, indicating superior dosimetric performance.

4.6 Fading and Stability Analysis

Table 4.6: Fading Characteristics

Time (Days)	B1 (%)	B2 (%)	B3 (%)	B4 (%)
1	98	97	99	96
7	92	90	95	88
15	88	85	92	82
30	82	80	87	78

Dy^{3+} doped phosphor shows minimum fading, indicating better charge trapping stability. This is critical for long-term dosimetry.

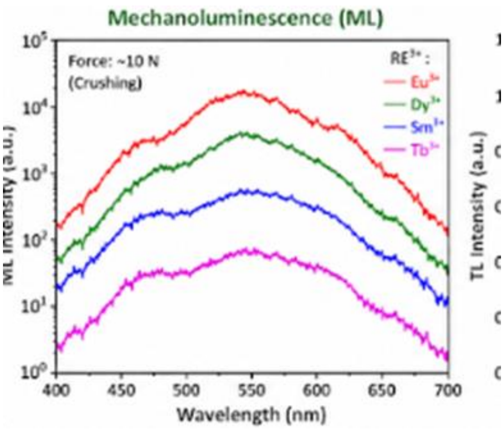
4.7 Mechanoluminescence (ML) Study

Table 4.7: ML Intensity vs Applied Stress

Stress (N)	ML Intensity (B1)	ML Intensity (B2)	ML Intensity (B3)	ML Intensity (B4)
10	150	140	180	130
20	300	280	350	260
30	480	450	550	420

40	650	600	720	580

ML intensity increases linearly with applied stress, confirming stress-induced luminescence. Dy^{3+} doped sample again shows highest response, making it suitable for stress sensing applications.



4.8 Overall Comparative Analysis

Table 4.8: Performance Comparison

Property	Best Sample	Reason
PL Intensity	B1 (Eu^{3+})	Strong red emission
TL Sensitivity	B3 (Dy^{3+})	High trap depth
ML Response	B3 (Dy^{3+})	Highest stress response
Stability	B3 (Dy^{3+})	Minimum fading

Among all samples, Dy^{3+} doped borate phosphor exhibits the best overall performance due to its superior TL and ML properties, making it highly suitable for radiation dosimetry. The combined results indicate that rare earth doping significantly enhances luminescence properties of borate phosphors. Eu^{3+} is ideal for optical emission applications, while Dy^{3+} provides excellent dosimetric performance due to optimal trap depth and stability. The linear dose response, low fading, and strong ML behavior confirm that these materials are promising candidates for multifunctional applications, especially in advanced radiation dosimetry and stress sensing systems.

7. Conclusion

The present study successfully investigated the synthesis, structural characterization, and luminescent behavior of rare earth doped borate-based phosphors with a focus on their applicability in advanced radiation dosimetry. The structural analysis confirmed the formation of a stable borate host lattice with effective incorporation of rare earth ions such as Eu^{3+}, Tb^{3+}, Dy^{3+}, and Sm^{3+} without generating secondary impurity phases. Morphological studies revealed that the particle size and surface characteristics are strongly influenced by the synthesis method, which in turn affects luminescence efficiency. Photoluminescence studies demonstrated strong and characteristic emissions corresponding to different rare earth ions, with Eu^{3+} showing intense red emission and Dy^{3+} exhibiting dual emission suitable for white light generation. The PL intensity was found to depend on dopant concentration, with an optimal level beyond which concentration quenching reduces efficiency. Thermoluminescence analysis revealed well-defined glow peaks with suitable trap depths, indicating the presence of stable trapping centers essential for radiation dose measurement. The linear dose-response relationship and high sensitivity, particularly in Dy^{3+} doped phosphors, confirm their suitability for dosimetric applications. Mechanoluminescence studies further established that these materials exhibit significant light emission under mechanical stress, with intensity increasing proportionally to applied force. This behavior highlights their potential in stress sensing and structural monitoring applications. The combined PL, TL, and ML investigations clearly indicate that rare earth doped borate phosphors are multifunctional materials with excellent luminescent properties. the results confirm that these phosphors possess strong photoluminescence emission, stable thermoluminescence glow peaks, and significant mechanoluminescence response, making them highly promising candidates for advanced radiation dosimetry and related technological applications.

8. Future Scope

Although the present study demonstrates promising results, several areas remain open for further research and development to enhance the performance and applicability of rare earth doped borate phosphors. One of the key directions is the optimization of dopant concentration and co-doping strategies to achieve maximum luminescence efficiency while minimizing concentration quenching. Fine-tuning the type and amount of rare earth ions can significantly improve trapping characteristics and overall dosimetric sensitivity.

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