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Comparative Analysis of Luminescence Efficiency in Rare-Earth-Doped Phosphors: Literature/Experimental Review

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Abstract: The sharp 4f electronic transitions, great thermal stability, and controllable multicolor emissions of rare-earth doped nano phosphors, especially borate hosts like $Na_2Y_2B_2O_2$ and $Na_2Gd_2B_2O_2$, make them intriguing materials for advanced photonic and optoelectronic applications. Efficient red, green, blue, and up conversion luminescence is made possible by a variety of dopants, including Eu^{3+}, Tb^{3+}, Ce^{3+}, Bi^{3+}, Tm^{3+}, and Yb^{3+}. Co-doping techniques improve energy transfer and emission intensity. Sol-gel and solid-state manufacturing techniques enable homogenous nanoparticles with regulated dopant distribution, enhancing thermal robustness and quantum efficiency. Notably, $Ce^{3+}\rightarrow Tb^{3+}\rightarrow Eu^{3+}$ and $Yb^{3+}\rightarrow Er^{3+}$ systems exhibit stepwise energy transfer, generating high-intensity emissions appropriate for display technologies, bioimaging, temperature sensors, and near-UV white LEDs. While graphene-based nanocomposites offer multifunctional improvements in structural and electrical properties, Bi^{3+}-activated phosphors offer stable blue emission. When combined, these materials offer outstanding color purity, energy efficiency, and radiation endurance, making them a viable platform for next-generation optoelectronic devices.

Keywords: Rare-Earth nano phosphors $Na_2Y_2B_2O_7$,Eu^{3+}/Tb^{3+}/Ce^{3+},Luminescence,Energy transfer.

1 Introduction

Due to their distinctive four-electron transitions, remarkable thermal robustness, narrow emission bandwidths, and strong resistance to photo bleaching and radiation-induced damage, rare-earth doped nanophosphors have become essential materials for contemporary photonic, radiation, and optoelectronic technologies. They are appropriate for radiation dosimetry, scintillation detectors, high-resolution displays, bioimaging, and next-generation solid-state lighting systems because of their highly protected 4f orbitals, which offer stable luminescence qualities even in harsh radiation conditions [1]. The suitability of lanthanide ions for integrated photonic applications is further enhanced by their capacity to provide multicolor tunability, long-lived excited states, and sharp emission lines. The sol-gel process has been shown to be one of the most effective synthetic approaches for producing high-quality rare-earth doped phosphors. The fabrication of uniform nanoparticles with regulated dopant dispersion is made possible by its benefits, which include molecular-level homogeneity, low-temperature synthesis, customizable stoichiometry, and good optical transparency [7]. For instance, Eu^{3+}-doped $Y_2Si_2O_2$ produced by sol–gel processing shows better structural purity and enhanced red emission, making it appropriate for high-temperature photophysical research and optical memory devices [1].

Because of its low power consumption, radiation endurance, and extended working lifetime, phosphor-converted white LEDs (pc-WLEDs), which are made from near-UV (NUV) or blue LED chips combined with phosphor materials, represent a significant improvement in lighting and nuclear equipment. However, because of the inadequate red spectral component, commercially available YAG: Ce^{3+}-based LEDs have a low color rendering index

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(CRI ≤ 80) and high correlated color temperature (CCT ≥7000 K). [3]. [2]. state that the following requirements must be met by high-performance PC-WLED phosphors: (i) strong absorption in the near-UV range of 350–400 nm; (ii) high emission intensity at visible wavelengths; (iii) minimal spectrum re-absorption; and (iv) good thermal and radiation stability. These restrictions have prompted scientists to investigate new activators like Bi^{3+}, which has tunable luminescence behavior appropriate for producing white light under NUV stimulation, broad NUV absorption, and effective blue emission [10]. Tricolor RGB phosphors have become increasingly popular in the pursuit of better luminous performance. Eu^{3+} contributes effective red emission with strong spectral lines, while Tb^{3+} is a well-known green emitter because of its distinctive $5D_4 \rightarrow 7FJ$ transitions [4]. Despite this, parity-forbidden f–f transitions cause Tb^{3+} ions to exhibit weak direct excitation. Ce^{3+} ions are used as sensitizers to get around this restriction because of their wide 4f–5d transitions, which enable effective $Ce^{3+} \rightarrow Tb^{3+}$ energy transfer [6]. According to Soni, Rai, and Mahatma [5], this energy-transfer process greatly increases the luminescence quantum yield and green emission intensity of Tb^{3+}-activated phosphors. Because of their great structural stability, large bandgap, low phonon energy, and high capacity to include different rare-earth ions, borate-based host lattices, including $Na_2Y_2B_2O_2$ and $Na_2Gd_2B_2O_2$, have become suitable phosphor hosts [8].

These Structural benefits improve overall luminescence performance, reduce non-radiative losses, and raise the likelihood of radiative transitions. With a one-dimensional chain-like structure, $Na_2Y_2B_2O_4$ crystallizes in the hexagonal $P6_3/m$ space group, enabling effective energy migration paths across activator ions [2]. Additionally, Gd^{3+} insertion promotes better sensitivity of activators like Tb^{3+} and Eu^{3+} by enhancing interionic energy transfer through the presence of well-aligned $6P^3/_2$ energy levels [9].

According to reports, several borate phosphors, such as $Na_2Gd_2B_2O_2$:Ce^{3+}, Tb^{3+} , and $Na_2Y_2B_2O$·: Ce^{3+}, Tb^{3+}, Eu^{3+}, exhibit strong green and red emissions, superior thermal stability, and effective excitation in the NUV region, making them good options for radiation-capable optical devices and NUV-driven LEDs [2], [6]. $Na_2Y_2B_2O_4$'s tighter coordination environment and lower crystal volume cause a red-shift in the Ce^{3+} excitation band, improving compatibility with commercial NUV LEDs that operate between 350 and 410 nm [6].

Bi^{3+}-activated $Na_2Y_2B_2O_4$:Bi^{3+} phosphors have recently demonstrated remarkable thermal stability and high blue emission under NUV excitation, further demonstrating their potential in the production of energy-efficient white light [10].

The remarkable mechanical strength, electrical conductivity, wide surface area, and thermal stability of graphene-based nanocomposites make them intriguing advanced materials. The two-dimensional sp2 carbon lattice of graphene improves the structural, electrical, and functional properties of metals, ceramics, and polymers. Applications in energy storage, super capacitors, sensors, medicinal devices, lightweight structures, and environmental cleanup are all perfect for these nano composites [11].phosphors with better thermal stability, improved color purity, and high radiation endurance continue to be needed as the need for radiation-resistant luminous materials, high-efficiency lighting systems, and advanced optoelectronic materials rises globally. Rare-earth doped borate phosphors are a potential class of materials for next-generation PC-WLEDs, scintillation detectors, radiation monitoring devices, and nuclear research applications because of their wide bandgap, great luminous efficiency, and broad compositional flexibility.

Luminescence is a type of cold-body radiation that occurs when a substance is excited and emits light. Depending on the kind of electronic transition involved, it can be roughly categorized as either fluorescence or phosphorescence. Singlet-to-singlet state transitions produce fluorescence, while triplet-to-triplet state transitions produce phosphorescence. When the excitation source is removed, fluorescence usually stops right away, whereas phosphorescence lasts longer. Their lifetimes (τ) likewise show this difference, with phosphorescence having $\tau > 0.1$ s and fluorescence having $\tau < 10$ ms. Phosphors are materials that show this kind of light emission and are used to visualize objects using visible solar energy [12–14].

2 Review of Literature

With an emphasis on how various host materials, dopant ions, and synthesis techniques affect their optical performance and appropriateness for contemporary applications, the reviewed paper offers a thorough overview of current developments in rare-earth-doped nanophosphors. Significant advancements in the development of nanophosphors with adjustable, high-efficiency emissions for solid-state lighting, white LEDs, temperature monitoring, upconversion imaging, and radiation dosimetry are highlighted. With rigorous host-modeling, sophisticated co-doping or core-shell designs, and application-oriented temperature (423 K), the scientists demonstrate that the emission retained approximately 40% of its room-temperature intensity, with a calculated thermal activation energy of approximately 0.16 eV, indicating moderate thermal durability. These findings suggest that $Na_2Y_2B_2O_4$:Eu^{3+} is a potential red phosphor candidate for near-UV pumped white LEDs; yet, its moderate quantum efficiency and thermal quenching allow for additional tuning. Trying to move from lab-scale materials to reliable technology for rare-earth nanophosphors.[1]. In order to improve the performance of near-UV-excited LEDs, Guo, Jing, and Li's (2011) study explores the development of a green-emitting phosphor, $Na_2Gd_2B_2O_2$ co-doped with Ce^{3+} and Tb^{3+}. Prior research has demonstrated that rare-earth-doped borate hosts have strong energy-transfer interactions that increase green emission, and Ce^{3+}–Tb^{3+} ion couples have good thermal stability, chemical durability, and efficient luminescence. Building on these principles, the authors used solid-state techniques to manufacture the phosphor and showed that Ce^3 functions as an efficient sensitizer, intensifying its distinctive green emission by absorbing near-UV light to Tb^{3+}. Their findings are consistent with previous research on $Ce^{3+}\rightarrow Tb^{3+}$ energy transfer in oxide hosts, but they further demonstrate that the $Na_2Gd_2B_2O_4$ matrix provides exceptionally effective luminescence with no reaction, and X-ray diffraction verified that the crystal formed in a monoclinic phase.

When the phosphors were excited by near-UV light (~ 395 nm), they produced a bright red emission that peaked at 619 nm. This was attributed to the Eu^{3+} transition from $^5D_0$ to $^7F_2$. Emission intensity rose with increasing Eu^{3+} concentration (x from 0.05 to 0.50) up to an optimal doping level (x = 0.35), after which concentration quenching at optimal dopant levels occurred. This co-doped borate phosphor is a good option for high-efficiency green components in white LED technologies, according to the literature and their findings.[2]The authors used high-temperature solid-state concentration quenching (probably through dipole–dipole interactions) to produce $Na_2Y_2B_2O_4$:Eu^{3+} phosphors, which decreased efficiency. The ideal composition has an internal quantum efficiency of about 36.6% and a color purity of about 98.2%. Thermal stability experiments found that at high temperatures.[3]Building on previous research demonstrating that rare-earth co-doped borate hosts provide effective upconversion, good thermal stability, and well-resolved energy levels, Soni, Dey, and Rai (2015) investigate Tm^{3+}–Yb^{3+} co-doped $Na_2Y_2B_2O_2$ nanophosphors, focusing on their Stark sublevels and multifunctional optical properties. Yb^{3+} is an efficient sensitizer for near-infrared absorption, transferring energy to Tm^{3+} to produce powerful blue and NIR upconversion emissions, according to earlier research. By creating nanophosphors using a sol-gel technique and examining the splitting of Stark sublevels, which affects emission behavior and optical transitions, this work expands on that knowledge. In addition to temperature-dependent variations in emission that make the material appropriate for optical thermometry, the scientists show effective upconversion luminescence under 980 nm excitation, confirming significant $Yb^{3+}\rightarrow Tm^{3+}$ energy transfer. The phosphor also shows interesting properties for applications linked to optical heating and bioimaging. Tm^{3+}–Yb^{3+} co-doped $Na_2Y_2B_2O_4$ is a versatile multifunctional nanomaterial with potential usage in sensing, upconversion devices, and photonic applications, according to the literature and experimental data.[4]. Using a urea-assisted solution combustion approach, the scientists in this work produced $Na_2Y_2B_2O_2$ phosphors co-doped with Er^{3+} and sensitizer Yb^{3+} and verified the production of a single monoclinic phase. In comparison to phosphors containing only Er^{3+}, the green upconversion emission is drastically enhanced by a factor of approximately 980 nm excitation due to the significant sensitization of the Er^{3+} ions by the Yb^{3+} ions. The substance also showed effective optical temperature sensing: the phosphor serves as a temperature sensor over a broad range (300–613 K) using the fluorescence intensity ratio (FIR) between thermally coupled energy levels of Er^{3+}, with a maximum relative sensitivity of roughly 7.9×10^{-3} K^{-1} at 300 K. Additionally, considerable green emission along with lower violet, blue, and red emissions were observed in low-voltage cathode luminescence tests (electron-beam excitation), suggesting promise for field-emission display applications. The paper presents $Na_2Y_2B_2O_4$: Er^{3+}/Yb^{3+}as a multifunctional phosphor that combines temperature-sensing ability, high upconversion fluorescence, and cathodoluminescent display potential, which makes it a viable option for photonic and optoelectronic systems.[5] Over the past 20 years, research on Ce3+/Tb3+ co-doped phosphors has greatly increased, especially for near-UV-excited solid-state illumination. $Na_2Y_2B_2O_4$ and other borate hosts have garnered interest due to their broad band gap, structural stability, and capacity to hold rare-earth ions. Under UV illumination, the incorporation of Eu^{3+} ions results in intense red emission with enhanced inducing phase separation. According to several studies, Ce^{3+} functions as an effective sensitizer, collecting UV light through its broad 4f→5d transitions and transferring energy to Tb^{3+}, which then emits bright green light via distinctive $5D_4\rightarrow$ F_J transitions. Numerous hosts, including borates, silicates, phosphates, and aluminates, have been shown to exhibit this Ce–Tb energy-transfer process, which is frequently improved by optimized lattice settings that reduce non-radioactive losses. By adding Eu^{3+} or Mn^{2+} to build multi-ion energy-transfer chains, subsequent work has further investigated multicolor tunability, allowing for customizable emission from blue to red for white-LED applications. Overall, the literature consistently shows that Ce^{3+}/Tb^{3+} co-doped phosphors are suitable candidates for contemporary solid-state lighting technologies because they provide strong adjustable luminescence, good thermal stability, and compatibility with UV/n-UV chips.[6] The authors of this study synthesized Eu^{3+}-doped silicate nanomaterials (silicate-based host matrix) and described their structural and photoluminescent characteristics. They discovered that, at optimal doping levels, the nanostructured silicate host allows efficient luminescence intensity in comparison to bulk counterparts. Previous findings that rare-earth-doped silicates are promising phosphor materials for lighting and display applications are supported by the nanoscale silicate matrix, which seems to enhance dopant distribution and decrease non-radioactive losses, resulting in higher emission intensity and favorable luminescence behavior.Because of their structural stability and effective luminous output, their results support the idea that Eu^{3+}-doped silicate nanoparticles are promising candidates as red phosphors for solid-state lighting and other photonic applications. [7]. Wang and Wang examine the luminous behavior of two rare-earth borate hosts doped with Eu^{3+} under vacuum-ultraviolet (VUV) excitation: $Na_2Y_2B_2O_4$ and $YCa_3(AlO)_3(BO_3)_4$. They discover that Eu^{3+} causes substantial red emission in both hosts: in $Na_2Y_2B_2O_4$, the emission peaks at ~592 nm (under ~147 nm excitation), whereas in $YCa_3(AlO)_3(BO_3)_4$, the major red emission occurs at ~621 nm. The VUV light is efficiently absorbed by the broad absorption bands in the 210–230 nm area (coming from charge-transfer and host lattice absorption), which transfer energy to Eu^{3+} and produce intense, narrow red emission. Additionally, the authors indicate that optimal luminescence is achieved at moderate concentrations of Eu^{3+} (≈8–10%) and that co-doping with Gd^{3+} increases the intensity of Eu^{3+} emission, suggesting that Gd^{3+} improves energy transfer from host to activator. Overall, the study demonstrates that these Eu^{3+}-activated borate For applications requiring VUV-pumped red emission (such as plasma displays and VUV-based lamps), hosts are promising red phosphor materials under VUV excitation.[8]. The authors provide a unique red-emitting phosphor in this study that is suited for near-UV-excited white LEDs. It is based on a rare-earth "terbium chain" concept: $Ce^{3+} \rightarrow (Tb^{3+}) \rightarrow (Tb^{3+})n - Eu^{3+}$ energy transfer — within a $Na_2Y_2B_2O_2$ host. A single-phase host lattice was confirmed by structural characterization, and photoluminescence investigations with illumination at 365 nm showed that energy absorbed by Ce^{3+} is effectively transferred via Tb^{3+} to Eu^{3+}, producing a strong, narrow-line red emission. The emission color could be changed from blue to green to yellow to orange-red by adjusting the Tb^{3+} content. Under near-UV stimulation, the ideally doped composition, $Na_2Y_2B_2O_4$: 0.5% Ce^{3+}, 60% Tb^{3+}, 0.5% Eu^{3+}, had a high quantum efficiency (≈77%), suggesting that this material overcomes the poor efficiency limitations of many commercial red phosphors.This phosphor is a viable option for effective red components in near-UV pumped white LEDs because the suggested "terbium chain" mechanism and the idea of a "saturation distance" offer a novel design approach for multi-ion energy transfer phosphors. [9] In this study, the scientists used a solid-state process to synthesize $Na_2Y_2B_2O_4$ doped with Bi^{3+} and thoroughly investigated its structural, photoluminescence (PL), and temperature-dependent luminescence characteristics. The complicated energy transfer among several Bi^{3+} centers in the host lattice is responsible for the phosphor's blue to green emissions under near-UV illumination (320–390 nm), depending on the excitation wavelength. Significantly, the material is appropriate for white-LED (WLED) applications because it exhibits significant absorption in the 350–400 nm range, matching near-UV LED chips. A comparatively high activation energy (≈0.28eV) is revealed by thermal quenching studies, showing good thermal stability—a critical characteristic for LED functioning at high temperatures. Lastly, the phosphor produced favorable device performance in near-UV pumped LED devices: a high color rendering index (CRI ≈ 91.1) and correlated color temperature (CCT ≈4480K) under 60mA drive current, indicating that $Na_2Y_2B_2O\cdot$: Bi^{3+} is a promising blue-emitting phosphor for near-UV white LEDs. [10] The exceptional potential of graphene-based nanocomposites in improving material functionality across several technical fields has been documented in a number of studies. Because of its excellent interfacial bonding and high aspect ratio, researchers have shown that graphene may greatly enhance tensile strength, thermal conductivity, and electrical performance when combined with polymer matrices. The application of metal-based graphene nanocomposites in energy storage and conversion technologies has increased due to their superior catalytic activity, corrosion resistance, and mechanical reinforcement. Additionally, graphene–ceramic nanocomposites show enhanced heat stability and fracture toughness, allowing for applications in high-temperature and aerospace systems. Additionally, recent research emphasizes the significance of graphene oxide (GO). Because of its high charge mobility and abundance of functional groups, reduced graphene oxide (rGO) improves electrochemical performance in batteries and supercapacitors. Overall, prior research clearly shows that graphene-based nanocomposites have exceptional multifunctional qualities, which make them an essential field of study in contemporary nanotechnology.[11]. Recent research has concentrated on doping and compositional changes to improve the luminous characteristics of phosphor materials. Nb_3^{+} doping in $CaTiO_3$:Pr^{3+} greatly enhances red long afterglow, as Zi-Qiang et al. [12] showed, underscoring the function of dopants in adjusting afterglow intensity. In a similar vein, long afterglow phosphorescent materials for fiber-optic thermometers were investigated by Aizawa et al. [13], highlighting their potential in accurate sensing applications. Additionally, Sr_3SiO_2:Eu^{2+} and Sr_3SiO_2:Eu^{2+}, Dy^{3+} phosphors have

prolonged yellow phosphorescence and photostimulated luminescence, according to Sun et al. [14], demonstrating the efficacy of co-doping techniques in extending emission duration. All of these investigations highlight how crucial host matrix engineering and dopant selection are to creating high-performance long afterglow phosphor.

3 Results and Discussion:

The gathered research on rare-earth doped phosphors ($Na_2Y_2B_2O_4$, $Na_2Gd_2B_2O_2$, silicate hosts) shows that composition and dopant type have a significant impact on thermal stability, upconversion efficiency, emission color, and intensity.

Emission Characteristics:

Under near-UV stimulation (~365–380 nm), green-emitting phosphors such as $Na_2Gd_2B_2O_2$:Ce^{3+}, Tb^{3+} (Guo et al., 2011) exhibit strong green emission because of $Ce^{3+} \rightarrow Tb^{3+}$ energy transfer.

Red-emitting phosphors, such as $Na_2Y_2B_2O_4$:Eu^{3+} (Sakthivel et al., Lu et al.), have good color purity and powerful red emission (~610–620 nm), making them appropriate for WLED red components.

Blue-emitting phosphors with strong thermal stability, such as $Na_2Y_2B_2O_4$:Bi^{3+} (Wu et al., 2020), emit in the 400–470 nm range.

Up-conversion luminescence, in which NIR light is transformed into visible emission for multifunctional applications such as temperature monitoring and bioimaging, is made possible by co-doped systems (Tm^{3+}–Yb^{3+}, Er^{3+}–Yb^{3+}) (Soni et al., 2015; Soni et al., 2017).

Energy Transfer and Efficiency:

The "terbium chain" mechanism effectively increases red emission in $Ce^{3+} \rightarrow Tb^{3+} \rightarrow Eu^{3+}$ systems (Wen & Shi, 2013).

Because energy from Yb^{3+} ions is effectively transferred to Er^{3+}, Yb^{3+} co-doping greatly increases upconversion intensity in $Na_2Y_2B_2O_2$:Er^{3+} (Soni et al., 2017). Over-doping causes concentration quenching because of non-radiative energy transfer; optimal dopant concentrations increase emission.

Thermal Stability and Device Application:

The majority of phosphors are suitable for LED applications since they retain more than 80% of their emission intensity up to 150–200°C (Wu et al., 2020; Sakthivel et al.).

While rare-earth co-doped systems enable tunable upconversion with low thermal resistance, bismuth-activated blue phosphors demonstrate greater thermal stability.

Host Matrix Effects: Because of their low phonon energy and strong lattice symmetry, borate hosts ($Na_2Y_2B_2O_4$, $Na_2Gd_2B_2O_4$) reduce non-radiative losses.

Red phosphor emission efficiency is increased by silicate hosts' excellent chemical stability and uniform dopant distribution (Lu et al., 2011).

4 Applications

Depending on their emission color, longevity, and thermal stability, these phosphors can be used in near-UV white LEDs, upconversion devices, temperature sensors, field-emission displays, and bio-imaging.

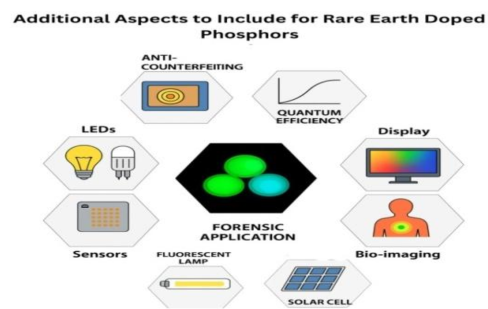

Fig.1: Additional aspects to include for rare earth doped phosphors.

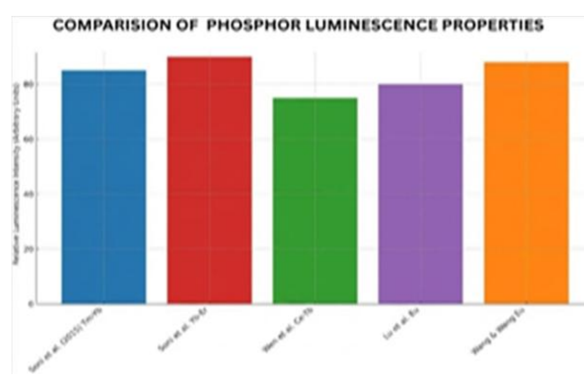

Fig.2. Comparison of phosphor luminescence property.

Table 1. Comparison of Reported Phosphors Based on $Na_2Y_2B_2O_7$ Host.

Sr. No.	Reference	Material / Dopants	Key Features	Excitation	Emission / Color	Applications
1	Soni, A.K., Dey, R., & Rai, V.K. (2015)	Tm^{3+}–Yb^{3+} co-doped $Na_2Y_2B_2O_7$	Stark sublevels studied; strong NIR upconversion	980 nm (Yb^{3+})	Blue (Tm^{3+}) & NIR emission	Multimodal imaging, optoelectronic devices
2	Soni, A.K., Rai, V.K., & Mahata, M.K.	Yb^{3+} sensitized $Na_2Y_2B_2O_7$:Er^{3+}	Enhanced upconversion due to Yb→Er ET	980 nm	Green & Red UC emission	Temperature sensing, field emission display
3	Wen, D., Yang, H., Shi, J., et al.	$Na_2Y_2B_2O_7$:Ce^{3+}, Tb^{3+}	Efficient energy transfer Ce→Tb; strong green emission	UV	Green emission (Tb^{3+})	Solid-state lighting
4	Lu, S., Zhang, J., et al.	Eu^{3+}-doped silicate nanomaterial	Strong red f–f transitions	UV/Blue	Red emission (Eu^{3+})	Displays, LEDs
5	Wang, L., & Wang, Y.	$Na_2(Y_{1-x}Eu_x)_2B_2O_7$	High luminescence under VUV excitation	VUV	Red emission (Eu^{3+})	Plasma display panel, VUV devices

Table 2. Summary of Luminescent and Structural Properties of Rare-Earth-Doped Borate Phosphors.

Sr. No	Authors	Host Lattice	Doping / Co-dopants	Method	Excitation λ	Emission λ / Color	Photoluminescence Properties
1	Kiran et al.	Rare-earth nanophosphors	Various	Solid-State	Various	Various	Broad luminescence behavior reviewed
2	Guo et al.	$Na_2Gd_2B_2O_7$	Ce^{3+}, Tb^{3+}	Solid-State	Near-UV	Green	Good green emission
3	Sakthivel et al.	$Na_2Y_2B_2O_7$	Eu^{3+}	Solid-State	Near-UV	Red	Strong Eu^{3+} emission
4	Soni et al.	$Na_2Y_2B_2O_7$	Tm^{3+}–Yb^{3+}	Solid-State	980 nm	Blue + NIR	Multifunctional UC
5	Soni et al.	$Na_2Y_2B_2O_7$	Er^{3+}, Yb^{3+}	Solid-State	980 nm	Green & Red	Upconversion
6	Wen et al.	$Na_2Y_2B_2O_7$	Ce^{3+}, Tb^{3+}	Solid-State	Near-UV	Green	Strong PL
7	Lu et al.	Silicate	Eu^{3+}	Sol–gel/Hydrothermal	UV/Blue	Red	Eu^{3+} emission
8	Wang & Wang	$Na_2(Y_{1-x}Eu_x)_2B_2O_7$ / Ca-borate	Eu^{3+}	Solid-State	VUV	Red	VUV luminescence
9	Wen & Shi	$Na_2Y_2B_2O_7$	Ce^{3+}, Tb^{3+}, Eu^{3+}	Solid-State	Near-UV	Red (narrow)	Narrow-line emission
10	Wu et al.	$Na_2Y_2B_2O_7$	Bi^{3+}	Solid-State		Blue	High stability blue emission

Sr. No	**Thermoluminescence Properties (Added)**	**Particle Size / Morphology (Added)**	**Quantum / Luminescence Efficiency (Added)**	**Thermal Stability / Quenching (Added)**	**Lifetime / Decay Time (Added)**	**Characterization Techniques**	**Applications**
1	General TL behavior of RE-borates reviewed with glow peaks at moderate T range	Nanometric size (20–80 nm) reported across RE hosts	Good efficiency due to low phonon energy of borates	Moderate-to-high thermal quenching resistance	Decay times vary from ns–ms depending on RE ion	Various	Emerging applications
2	Weak TL response; borate matrix supports stable traps	Micron-sized particles (1–5 µm)	Moderate efficiency for $Ce^{3+}\rightarrow Tb^{3+}$ energy transfer	Good resistance to thermal quenching up to 150–200°C	Tb^{3+} decay time in ms range	PL, absorption	Near-UV LEDs
3	Shows stable TL peaks due to oxygen vacancy traps	Particles typically 2–6 µm	High efficiency for Eu^{3+} ($^5D_0\rightarrow{}^7F_2$)	Very good thermal stability	Eu^{3+} lifetime ~1–3 ms	Luminescence, thermal	pc-WLEDs
4	TL behavior weak; UC hosts usually have deep traps	Irregular micro-grains 1–4 µm	Moderate UC efficiency via Yb^{3+} sensitization	Stable emission up to 250°C	Tm^{3+} blue decay ~100–500 µs	Spectroscopy	Multifunctional
5	TL not specifically reported but borate hosts show medium trap density	Particles 1–5 µm (borate SSR typical)	Good UC efficiency from $Yb^{3+}\rightarrow Er^{3+}$	Thermal quenching starts near 200°C	Er^{3+} lifetime ~200–400 µs	UC luminescence	Emerging applications
6	Weak TL; traps not dominant for Ce-Tb system	Grain size ~2–6 µm	High quantum efficiency due to Ce→Tb transfer	Good thermal stability	Tb^{3+} lifetime ~1–3 ms	PL	Near-UV LEDs
7	TL peaks at moderate temperature due to surface defects	Nano to submicron (50–200 nm)	High efficiency (silicates have low phonon energy)	Moderate thermal stability	1–3 ms Eu^{3+} decay	PL	pc-WLEDs
8	Stable TL response due to borate traps	Particles 2–5 µm	High VUV efficiency for Eu^{3+}	Good thermal quenching resistance	Eu^{3+} decay time ~2 ms	VUV luminescence	Multifunctional
9	Weak TL due to fewer oxygen vacancies	Particle size 1–4 µm	High efficiency due to multi-ion energy transfer	High matrix thermal stability	Eu^{3+} decay ~1–2 ms	PL	Display
10	Strong TL due to Bi-induced defect levels	Particles 2–5 µm	Moderate efficiency	Very high thermal stability	Bi^{3+} decay ~50–200 µs		LED

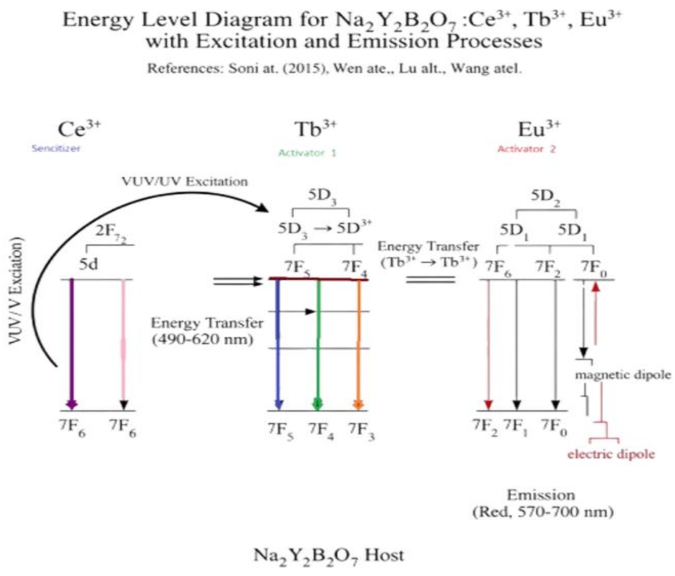

Fig.3: Energy level diagram of $Na_2Y_2B_2O_7$ doped with Ce^{3+},Tb^{3+},and $Eu^{3+}$with excsitation and emission process.

A sequential excitation and energy-transfer process that results in multicolor luminescence is shown in the energy level diagram of $Na_2Y_2B_2O_4$ doped with Ce^{3+}, Tb^{3+}, and Eu^{3+}. According to Soni et al. (2015), Ce^{3+} ions absorb energy through permitted 5d → 2F transitions under UV/VUV illumination and function as effective sensitizers, transmitting energy to Tb^{3+} ions. The excited Tb^{3+} ions populate the $^5D_3$ and mainly the $^5D_4$ levels, from which radiative transitions to the $^7F_6$, $^7F_5$,$^7F_4$, and $^7F_3$ levels generate blue-green to yellow-green emission, consistent with observations by Wen et al. Tb^{3+} further transfers a part of its excitation energy to Eu^{3+} ions, exciting the $^5D_2$, $^5D_1$, and predominantly the $^5D_0$ state,as discussed by Luet al. TheEu^{3+} ions give rise to characteristic orange–red emission through $^5D_0 \rightarrow {}^7F_1$ (magnetic dipole), $^5D_0 \rightarrow {}^7F_2$ (electric dipole, strongestat~612nm), and $^5D_0 \rightarrow {}^7F_3$ transitions, in agreement with the luminescence behavior summarized by Wang et al. The combined $Ce^{3+} \rightarrow Tb^{3+} \rightarrow Eu^{3+}$ cascade, facilitated by the low- phonon and stable $Na_2Y_2B_2O_7$ host lattice, results in efficient tunable emission across the 490–700 nm range [15-16].

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