

Recent progress and investigation of the RE-activated borate-based phosphors for w-LED applications

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Abstract

Phosphor-converted white-light-emitting diodes (pc-wLEDs) are widely used in solid-state lighting, but their performance depends strongly on the excitation compatibility, quantum efficiency, thermal stability, chromaticity, and color-rendering properties of the phosphor. Rare-earth (RE) ions offer versatile luminescent transitions, while borate hosts provide structurally diverse BO_3/BO_4 networks and compositional flexibility, making them attractive for UV/near-UV-excited white emission. This review critically examines recent advances in RE-activated borate phosphors, focusing on host engineering, activator selection, co-doping, energy transfer, defect regulation, thermal stability, and colorimetric performance. Representative Ce^{3+} , Eu^{2+}/Eu^{3+} , Tb^{3+} , Dy^{3+} , Sm^{3+} , Pr^{3+} , and multi-ion systems are discussed, with emphasis on the persistent challenges of concentration and thermal quenching, spectral imbalance, excitation mismatch, and reproducibility. The review highlights the need to establish unified structure–luminescence–thermal relationships and to evaluate phosphors under realistic LED operating conditions. These insights provide design guidelines for developing efficient, thermally stable, and color-tunable RE-activated borate phosphors for next-generation w-LEDs.

Keywords: borate phosphors; rare-earth ions; photoluminescence; thermal quenching; concentration quenching; white LEDs; color rendering; CCT

1. Introduction

The transition from conventional incandescent and fluorescent illumination toward solid-state lighting has made phosphor science increasingly central to the performance of modern white-light sources. Phosphor-converted white light-emitting diodes (pc-wLEDs) combine a semiconductor LED chip with one or more down-conversion phosphors that transform part of the high-energy pump radiation into longer-wavelength visible light. Their compact architecture, low operating voltage, long lifetime and high efficiency have supported widespread use in general illumination and related optical technologies, yet the spectral distribution, thermal reliability and color quality of commercial devices remain materials-dependent constraints [1–3]. In the conventional blue-chip/YAG:Ce³⁺ architecture, the broad yellow emission of Ce³⁺ activated garnet is combined with residual blue emission from an InGaN-type chip. This architecture is technologically mature, but its spectrum can contain insufficient red content, leading to elevated correlated color temperature (CCT) and limited color rendering in applications requiring warm or high-quality white light [4,5,23]. Consequently, phosphors that can absorb UV, near-UV (n-UV) or blue radiation efficiently and convert it into balanced visible emission remain an active research target.

An ideal phosphor for pc-wLED operation must satisfy several requirements simultaneously rather than excel in only one spectroscopic parameter. Efficient absorption at the emission wavelength of the selected LED chip is necessary for practical excitation; high internal and external quantum efficiencies are needed to minimize energy loss; and the emission spectrum must provide an appropriate combination of blue, green/yellow and red components for the intended white-light point. The phosphor must also resist thermal quenching under the elevated temperatures experienced during high-power operation, retain chemical and structural integrity during prolonged exposure to excitation, and remain compatible with phosphor packaging and processing. Colorimetric parameters such as CIE chromaticity, CCT and color-rendering metrics must be interpreted together with photometric and thermal behavior because a material with intense laboratory photoluminescence is not automatically an efficient or stable device phosphor [2,3]. This distinction is especially important for single-component white emitters, for which several emission channels must remain spectrally balanced over the operating temperature range.

Rare-earth ions are particularly attractive activators because their partially filled 4f shells generate characteristic intra-4f transitions with relatively sharp spectral signatures, while ions such as Ce³⁺ and Eu²⁺ can provide broader 5d–4f emission that is strongly influenced by the host crystal field. In trivalent lanthanides, 4f–4f transitions are largely shielded by outer 5s and 5p

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electrons, so their energies are comparatively insensitive to the host compared with d-state transitions, although intensity, Stark splitting, site symmetry and non-radiative relaxation remain host-dependent. Ce^{3+} and Eu^{2+} are especially useful as sensitizers or broad-band emitters because their allowed 5d–4f transitions can couple efficiently with UV or near-UV excitation. Eu^{3+} provides narrow red emission, particularly from the $^5\text{D}_0$ level to the $^7\text{F}_J$ manifold, while Tb^{3+} and Dy^{3+} offer green and blue/yellow components, respectively. Sm^{3+} contributes orange-red emission, and Pr^{3+} , Er^{3+} , Tm^{3+} and Yb^{3+} provide additional channels for spectral conversion and energy-transfer engineering [6,7,22].

The usefulness of an RE ion therefore cannot be separated from its host environment. Local coordination, crystallographic site symmetry, bond covalency, crystal-field strength, phonon energy, band structure and defect populations influence excitation probability, radiative transition rates and non-radiative relaxation. In co-doped systems, the host also determines whether the donor emission overlaps sufficiently with an acceptor absorption band to permit energy transfer. When donor and acceptor concentrations become too high, however, cross-relaxation, migration to quenching centers or multipolar interactions can reduce emission intensity. The resulting concentration quenching is not simply a universal concentration threshold; it reflects the spatial distribution of activators, the number and nature of available crystallographic sites, and the strength of ion–ion interactions. Similarly, thermal quenching results from thermally assisted non-radiative pathways whose accessibility depends on the electronic structure and lattice dynamics of the phosphor [6,8]. Rational phosphor design consequently requires a connection between crystal chemistry and photophysics rather than empirical dopant optimization alone.

Borate hosts occupy a distinctive position within this design landscape because boron can adopt both trigonal BO_3 and tetrahedral BO_4 coordination, producing a large variety of isolated, polymerized and mixed borate structural units. Corner-sharing of these units generates diverse anionic frameworks and allows alkaline-earth, rare-earth, alkali, transition-metal and other cations to be incorporated into chemically distinct sites. Such structural diversity creates opportunities for controlling activator coordination and separation, local symmetry and lattice rigidity. Borates are also valued for broad optical transparency, relatively large band gaps in many compositions, chemical and thermal stability, and compositional flexibility [6–9]. These characteristics have supported their use in orthoborates, aluminoborates, borophosphates, haloborates, mixed-metal borates and borate glasses. The same structural flexibility, however, makes the relationship between composition and luminescence complex: nominally similar borates can contain substantially different site geometries, phonon spectra, defect populations and energy-transfer pathways.

Compared with silicates, aluminates, phosphates, tungstates, molybdates, vanadates, nitrides and sulfides, borates offer a useful combination of structural diversity and chemical stability, but they are not universally superior. Nitrides, for example, can provide highly efficient broadband Eu^{2+} emission and excellent thermal robustness, although their synthesis often requires demanding reducing conditions and high temperatures. Sulfides can offer intense broad emission but may suffer from chemical instability. Phosphates and silicates provide well-developed host families with strong chemical durability, while tungstate and molybdate lattices can offer charge-transfer-related excitation and broad spectral tunability. The practical value of a borate host therefore depends on whether its particular crystal structure provides efficient excitation, suitable activator sites, low non-radiative losses and manageable synthesis. A key research question is not whether borates are intrinsically better than all other host classes, but which structural motifs within the borate family provide the most favorable combination of these properties.

Recent research illustrates the breadth of strategies used to address this question. Eu^{3+} activated borates have received sustained attention because commercial white LEDs commonly require stronger red spectral content. A notable example is $\text{Ca}_3\text{Eu}_2\text{B}_4\text{O}_{12}$, a fully Eu-substituted borate prepared by solid-state synthesis. Under approximately 393 nm excitation it exhibits strong red emission centered near 615 nm, and the reported quantum yield reached 95.6%; a warm pc-WLED assembled with the phosphor and commercial blue/green components achieved $R_a = 83.7$ and CCT around 3883 K [10]. The significance of this work extends beyond the numerical

values: it showed that an appropriately designed borate lattice can suppress the usual concentration-quenching penalty even at high Eu^{3+} content. Such behavior challenges the assumption that increased activator concentration must inevitably lead to strong quenching and highlights the importance of activator arrangement and host topology.

Eu^{3+} has also been incorporated into $\text{YAl}_3(\text{BO}_3)_4$ through lower-temperature solution combustion synthesis. Yadav and co-workers reported one-step synthesis at 500 °C using urea and glycine as fuels, producing a red-emitting phosphor with a prominent 614 nm band under 395 nm excitation [11]. The near-UV compatibility is relevant to n-UV-pumped devices, while the reduced synthesis temperature illustrates the potential of combustion routes to lower processing time and energy demand. Yet combustion synthesis also requires careful control of fuel/oxidant ratios and reaction homogeneity, and a low synthesis temperature by itself does not establish industrial scalability or superior device reliability. The broader lesson is that preparation route and phosphor performance must be evaluated together.

Ce^{3+} and Tb^{3+} containing borates illustrate a different design philosophy in which a broad-band donor sensitizes a narrow-band activator. In $\text{Ba}_2\text{Gd}_5\text{B}_5\text{O}_{17}$, $\text{Ce}^{3+}/\text{Tb}^{3+}$ co-doping produced efficient $\text{Ce}^{3+} \rightarrow \text{Tb}^{3+}$ energy transfer and blue-green color-tunable emission under 345 nm excitation [12]. Such systems exploit the allowed Ce^{3+} 5d–4f transition to capture n-UV photons and then transfer excitation to Tb^{3+} , whose characteristic green emission can be adjusted by changing the acceptor concentration. The approach is attractive for n-UV WLEDs because it avoids reliance on a single ion to satisfy both excitation and emission requirements. Its limitation is that donor-to-acceptor transfer must compete with donor radiative decay, host trapping and non-radiative relaxation; excessive acceptor concentration can introduce migration and concentration quenching. Thus, a spectroscopically confirmed energy-transfer pathway is useful, but it does not by itself guarantee high quantum efficiency or thermal stability in a device.

Dy^{3+} provides an especially interesting route toward single-phase white emission because its $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$ blue and $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$ yellow transitions can together occupy complementary regions of the visible spectrum. However, the relative blue/yellow intensity is sensitive to the local symmetry around Dy^{3+} , and the yellow transition is comparatively hypersensitive to the host environment. Concentration quenching and thermal redistribution can therefore disturb the balance needed for white light. In a 2023 study of Dy^{3+} doped $\text{Ca}_3\text{LuAl}_3\text{B}_4\text{O}_{15}$, structural control was used to obtain single-phase white emission with CIE coordinates near (0.36, 0.39) and a CCT of approximately 4624 K in a fabricated WLED [13]. Other Dy^{3+} containing borate systems have shown that co-doping with Eu^{3+} can add a red channel and permit a transition from cool to warm white emission. $\text{Gd}_5\text{Si}_2\text{BO}_{13}:\text{Dy}^{3+}, \text{Eu}^{3+}$, for example, used $\text{Dy}^{3+} \rightarrow \text{Eu}^{3+}$ energy transfer to tune CCT from about 5475 to 2128 K while retaining useful thermal and environmental stability [14]. These studies demonstrate the practical value of spectral complementation, but they also show that white emission is a balance problem: adding a red activator may improve CCT and color rendering while simultaneously changing excitation pathways, energy-transfer efficiency and thermal behavior.

The recent development of multi-activator borates has made this balancing strategy more explicit. $\text{Ca}_3\text{LuAl}_3\text{B}_4\text{O}_{15}:\text{Bi}^{3+}, \text{Tb}^{3+}, \text{Eu}^{3+}$ provided blue, green and red contributions from a single host. By tuning the three dopant concentrations, a warm-white point at CIE (0.3728, 0.3166), CCT 3671 K and Ra 87 was reported; a UV-chip device retained favorable performance after high-temperature aging [15]. The material illustrates how a non-rare-earth ion such as Bi^{3+} can serve simultaneously as a blue emitter and sensitizer, while Tb^{3+} provides an intermediate green-emitting/energy-transfer stage and Eu^{3+} supplies red emission. Such a cascade can improve spectral completeness, but every added activator introduces additional variables: site competition, charge compensation, cross-relaxation and multiple thermal-quenching channels. Consequently, the apparent compositional freedom of multi-doped borates is accompanied by a rapidly expanding optimization space.

More recent studies reinforce the shift from single-ion optimization toward coupled energy-transfer and structure engineering. $\text{KBaLu}(\text{BO}_3)_2:\text{Ce}^{3+}, \text{Mn}^{2+}, \text{Tb}^{3+}$ was designed to generate blue, green and red components through $\text{Ce}^{3+} \rightarrow \text{Mn}^{2+}/\text{Tb}^{3+}$ energy transfer. A single-phase composition produced a WLED with CRI 87.1 and CCT 5090 K, demonstrating that a carefully

selected donor can feed more than one acceptor and generate multi-band emission under n-UV excitation [16]. In another recent example, $\text{Ba}_3\text{Y}_2\text{B}_6\text{O}_{15}:\text{Dy}^{3+}/\text{Eu}^{3+}$ combined defect-related self-emission with $\text{Dy}^{3+} \rightarrow \text{Eu}^{3+}$ energy transfer. The authors linked its thermal robustness to the dense, highly symmetric lattice, high band gap and relatively weak electron–phonon coupling, while demonstrating a high-quality n-UV-pumped pc-wLED using a 350 nm chip [17]. This is particularly instructive because it connects defects, crystallographic order, energy transfer and device packaging rather than treating them as independent variables.

The newest literature is also moving toward systematic control of color and thermal response. $\text{Sr}_3\text{Dy}_{2-2x}\text{Eu}_{2x}(\text{BO}_3)_4$ was reported in 2025 as a new rare-earth borate family in which the $\text{Eu}^{3+}/\text{Dy}^{3+}$ ratio and excitation wavelength tune the emission from yellow-white toward yellow-pink. A composition with CIE coordinates of (0.3292, 0.3536) was close to standard white illumination, while the optimized sample retained more than 75% of its room-temperature emission at 150 °C [18]. In 2026, $\text{Dy}^{3+}/\text{Sm}^{3+}$ co-doped $\text{Na}_2\text{Y}_2\text{TeO}_4(\text{BO}_3)_2$ demonstrated $\text{Dy}^{3+} \rightarrow \text{Sm}^{3+}$ energy transfer governed by electric dipole–dipole interaction, with excitation-dependent yellow-to-orange-red tuning and approximately 90% emission retention at 425 K; integration with a commercial red phosphor and a 365 nm chip produced a WLED with CCT 6283 K and Ra 82 [19]. A separate 2026 $\text{Tb}^{3+}/\text{Eu}^{3+}$ study reported efficient $\text{Tb}^{3+} \rightarrow \text{Eu}^{3+}$ transfer in $\text{Sr}_5\text{MgLa}_2(\text{BO}_3)_6$, enabling green-to-red tuning; the optimized material had a reported quantum efficiency of 86.1%, retained 74.46% intensity at 423 K, and was used in a WLED with CCT 5480 K and CRI 91 [20]. These results indicate clear progress, but they also reveal that many high-performing demonstrations still rely on a combination of phosphors or specific excitation conditions rather than a universally robust single-component material.

2. Host–activator design and photophysical mechanisms

The performance of an RE-activated borate can be viewed as a chain linking host structure to practical device behavior:

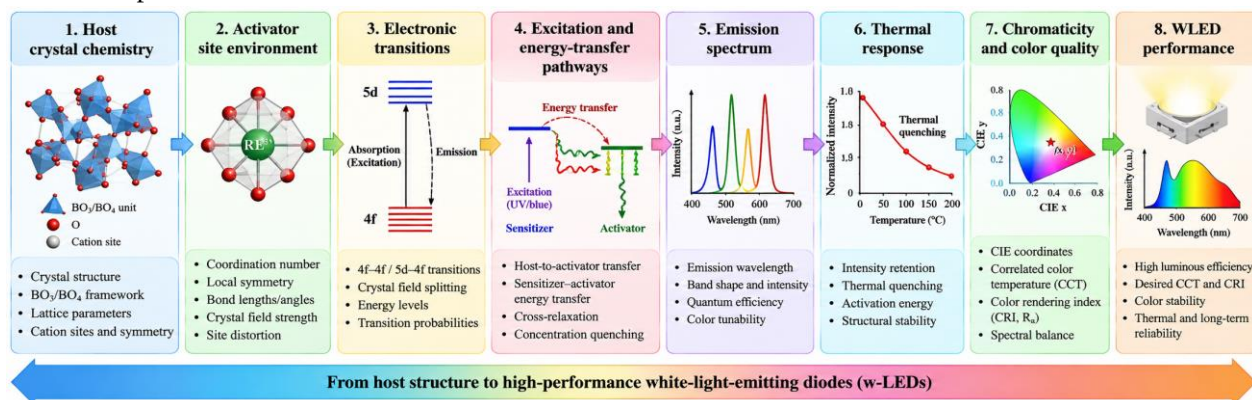


Figure 2. Structure–property–performance pathway of RE-activated borate phosphors for w-LEDs.

Breaking this chain at any point can reduce practical efficiency. For example, an activator may possess a favorable emission transition but weak absorption at the selected LED wavelength. Conversely, a phosphor with strong absorption can lose efficiency if the excited state is rapidly transferred to defects or dissipated through multiphonon relaxation. The central design challenge is therefore to maximize radiative conversion while minimizing parasitic channels.

2.1 Rare-earth activators and excitation pathways

Ce^{3+} and Eu^{2+} are attractive broad-band emitters because their 5d states are sensitive to crystal-field strength and therefore can be shifted across the UV-visible region by host engineering. This flexibility can be beneficial for matching blue or n-UV chips, but it also makes their spectra more host-dependent than the narrow 4f–4f transitions of many trivalent lanthanides. Eu^{3+} , Tb^{3+} , Dy^{3+} and Sm^{3+} provide more spectrally stable line emissions, which can improve color purity but can make efficient excitation more difficult because many 4f–4f transitions are parity-forbidden and comparatively weak. Sensitization by Ce^{3+} , Bi^{3+} , host-to-activator transfer or another donor can compensate for this limitation. In practice, the best activator is therefore

determined by the complete excitation–emission pathway rather than the nominal color of its strongest line.

Dy³⁺ is especially useful for white-light generation because its blue and yellow transitions can overlap complementary spectral regions. Eu³⁺ is a natural red complement to Dy³⁺, and Tb³⁺ can supply green emission. Sm³⁺ can shift the spectrum toward orange-red and is useful where warmer emission is required. Pr³⁺, Er³⁺, Tm³⁺ and Yb³⁺ broaden the design space further, particularly when upconversion or near-infrared conversion is desired, although such mechanisms are generally more complex and are not automatically advantageous for conventional down-conversion WLEDs. The selection of RE ions should consequently be based on energy-level alignment, absorption cross-section, host-site preference, phonon environment and desired spectral balance.

2.2 Energy transfer and concentration quenching

Co-doping can be beneficial when donor emission overlaps acceptor absorption and the donor–acceptor distance is sufficiently small. Energy transfer may proceed through exchange interaction or multipolar coupling, commonly electric dipole–dipole interactions in dilute lanthanide systems. Experimental confirmation normally combines excitation/emission spectral overlap with donor lifetime shortening and concentration-dependent intensity analysis. A reduction in donor lifetime after acceptor introduction is particularly informative because it demonstrates an additional depopulation channel rather than simply spectral overlap.

The same ion–ion interactions that enable useful energy transfer can become detrimental at higher concentration. Excitation migration can eventually reach quenching centers, while cross-relaxation can populate non-emissive levels. The critical concentration therefore depends on host topology and activator separation rather than on a universal molar percentage. The Ca₃Eu₂B₄O₁₂ case is important because it demonstrates that a carefully engineered lattice can tolerate unusually high Eu³⁺ loading without conventional concentration quenching [10]. This suggests that controlling site connectivity and activator distribution may be more powerful than simply lowering dopant concentration.

2.3 Thermal quenching

Thermal quenching is a major limitation for high-power LEDs because junction and phosphor temperatures can rise substantially during operation. As temperature increases, thermally activated non-radiative pathways can compete with radiative emission, producing intensity loss and sometimes spectral shifts. The activation energy derived from Arrhenius-type analysis is a useful comparative parameter, but it should not be treated as a complete descriptor of device stability. The measured thermal behavior also depends on excitation density, particle morphology, packaging, surface states and the particular emission channel being monitored.

Rigid borate frameworks can help suppress thermal losses, particularly when activators occupy well-confined sites in lattices with high connectivity and relatively weak electron–phonon coupling. However, borate chemistry alone does not guarantee thermal robustness. Defects, vacancies and compositional disorder can create trapping states or non-radiative pathways. The Ba₃Y₂B₆O₁₅:Dy/Eu system provides a useful example in which dense connectivity and structural symmetry were linked to high thermal stability [17]. The 2026 Dy/Sm borate study similarly demonstrated unusually strong temperature retention, but the result was obtained for a particular host and composition and should not be generalized to all borates [11].

3. Synthesis strategies and their implications

High-temperature solid-state synthesis remains the most common route for crystalline borate phosphors because it is conceptually simple and can produce phase-pure powders. Its disadvantages include repeated grinding, relatively high calcination temperatures, possible boron volatilization, broad particle-size distributions and sensitivity to precursor homogeneity. These factors can influence defect concentration and activator distribution, meaning that synthesis history can become an unrecognized variable in luminescence comparisons.

Combustion synthesis provides a lower-temperature and faster alternative. The YAl₃(BO₃)₄:Eu³⁺ study discussed above demonstrated one-step synthesis at 500 °C [21]. Solution-based methods such as sol–gel processing can improve chemical homogeneity and reduce diffusion distances, while hydrothermal and microwave-assisted approaches can shorten crystallization times or

modify particle morphology. Flux-assisted synthesis can improve crystallinity and reduce the temperature required for phase formation, but residual flux and impurity phases must be carefully controlled. For industrial relevance, a synthesis method should therefore be judged by more than its lowest processing temperature: phase reproducibility, precursor cost, batch-to-batch consistency, particle morphology, environmental burden and scalability are equally important.

For borate glasses, melt-quenching provides a compositionally flexible route and avoids the need for long-range crystalline order. This can be advantageous for accommodating RE ions at multiple local environments, although the same site disorder can broaden spectral features and complicate structure–property analysis. Recent Dy³⁺ activated borate glass work used Judd–Ofelt analysis to connect local asymmetry with radiative properties and white-light chromaticity [11]. Such studies illustrate the complementary value of glass and crystalline hosts: glasses offer compositional flexibility and facile processing, whereas crystals can provide better-defined activator sites and more direct structure–luminescence relationships.

4. Recent progress by activator and design strategy

Table 1 summarizes representative borate-based developments that illustrate the main design directions.

System	Principal strategy	Representative outcome	Limitation
Ca₃Eu₂B₄O₁₂:Eu³⁺	High Eu ³⁺ loading / host engineering	Red emission at ~615 nm; quantum yield of 95.6%; warm pc-wLED with R _a = 83.7 and CCT ≈ 3883 K [10]	Primarily functions as a red-emitting component; does not provide a complete single-phase white-light solution
Ba₂Gd₅B₅O₁₇:Ce³⁺/Tb³⁺	Sensitizer–activator energy transfer	Blue-to-green emission tunability under 345 nm excitation [12]	Limited spectral coverage; an additional red component is required for high-quality white light
Ca₃LuAl₃B₄O₁₅:Bi³⁺/Tb³⁺/Eu³⁺	Three-ion spectral complementarity	Warm-white emission with CIE coordinates (0.3728, 0.3166), CCT = 3671 K, and R _a = 87 [15]	Multi-ion optimization increases compositional complexity and requires precise dopant control
Gd₅Si₂BO₁₃:Dy³⁺/Eu³⁺	Dy ³⁺ → Eu ³⁺ energy transfer	CCT tunable from ~5475 to 2128 K; good thermal, UV, and moisture stability reported [14]	Energy-transfer efficiency and spectral balance depend strongly on Eu ³⁺ concentration
KBaLu(BO₃)₂:Ce³⁺/Mn²⁺/Tb³⁺	Multi-step energy transfer	Single-phase WLED performance with CRI = 87.1 and CCT = 5090 K [16]	Multiple acceptors introduce competing relaxation and energy-transfer pathways
Ba₃Y₂B₆O₁₅:Dy³⁺/Eu³⁺	Defect engineering + Dy ³⁺ → Eu ³⁺ energy transfer	Demonstrated nUV-pc-wLED application with high thermal stability [17]	Reproducible control of defect chemistry is essential for consistent luminescence
Sr₃Dy_{2-2x}Eu_{2x}(BO₃)₄	Dy ³⁺ /Eu ³⁺ compositional tuning	White emission near CIE (0.3292, 0.3536); >75% emission intensity retained at 150 °C [18]	Emission color is sensitive to excitation wavelength and dopant composition
Na₂Y₂TeO₄(BO₃)₂:Dy³⁺/Sm³⁺	Dy ³⁺ → Sm ³⁺ energy transfer	~90% emission intensity retained at 425 K; WLED with CCT = 6283 K and R _a = 82 [19]	Practical WLED implementation required an additional commercial red phosphor
Sr₅MgLa₂(BO₃)₆:Tb³⁺/Eu³⁺	Tb ³⁺ → Eu ³⁺ energy transfer	Quantum efficiency of 86.1%; WLED performance with CRI = 91 and CCT = 5480 K [20]	Thermal retention and excitation compatibility remain dependent on the specific application conditions

The progression visible in Table 1 is significant. Early work often focused on obtaining a strong red, green or yellow emission from a single activator. More recent studies increasingly treat the phosphor as a spectral-conversion network, where donors, acceptors and defect states are deliberately coupled. This shift is scientifically productive because white light requires broadband spectral coverage, but it also raises the burden of characterization. A convincing multi-ion phosphor should ideally be supported by structural refinement, site-occupancy analysis, excitation/emission mapping, lifetime measurements, temperature-dependent spectra and quantitative colorimetry. Without this combination, an apparent color change may be attributed to energy transfer when it is partly caused by changing defect populations or site occupancy.

5. Structure property relationships and the remaining knowledge gap

The literature establishes that host structure matters, but the relationship is not yet sufficiently unified to allow reliable prediction of phosphor performance across the borate family. Similar RE ions can display different excitation bands, emission ratios and quenching temperatures in chemically related hosts because the activator may occupy different sites or experience different coordination numbers. Conversely, different hosts can sometimes produce similar optical output when the local RE environment is comparable. This indicates that global composition alone is an incomplete descriptor.

A more useful framework is to distinguish at least four structural levels. First, the borate network controls rigidity, phonon behavior and connectivity. Second, the crystallographic site controls activator coordination, symmetry and local crystal field. Third, the spatial distribution of activators controls energy migration and cross-relaxation. Fourth, defects and interfaces provide additional trapping and non-radiative channels. The resulting luminescence is an emergent property of these levels rather than a direct consequence of dopant identity.

Several knowledge gaps follow. The first is the incomplete correlation between refined site occupancy and measured photoluminescence. Many studies establish phase purity by powder XRD but do not fully resolve which RE ion occupies which crystallographic site. The second is the limited comparability of thermal-stability data because different studies use different temperatures, excitation powers, definitions of retention and emission bands. The third is the insufficient distinction between intrinsic phosphor quantum efficiency and packaged-device performance. A material may have high quantum yield but still be unsuitable for a given LED chip if its excitation band is poorly matched, its emission reabsorbs strongly, or its thermal behavior differs under high excitation density.

A fourth gap concerns concentration quenching. It is often described using critical concentrations and multipolar interaction models, but the physical origin of quenching may involve a combination of activator migration, defects, site occupation and clustering. The growing number of high-concentration borates, including $\text{Ca}_3\text{Eu}_2\text{B}_4\text{O}_{12}$ [10], suggests that lattice topology deserves more attention as a quenching-suppression variable. A fifth gap is the limited systematic comparison among RE activators within the same host family. Direct comparisons could reveal whether a host is intrinsically favorable or simply optimized for one particular dopant.

A sixth gap concerns device realism. Many publications report CIE coordinates and CCT from powder photoluminescence and describe potential WLED application, whereas only a subset fabricate and age actual LED packages. Device-level tests should ideally include luminous efficacy, spectral stability, operating temperature, long-term aging and reproducibility. Material-level CIE coordinates should not be interpreted as direct equivalents of device color coordinates because packaging geometry, scattering, residual chip emission and phosphor loading modify the final spectrum.

6. Toward rational design of high-performance borate phosphors

A rational design strategy should begin with the target LED chip rather than with the activator ion alone. If a 365–405 nm n-UV chip is selected, the phosphor should possess strong absorption across the relevant excitation band and convert it into complementary visible wavelengths [5]. If a blue chip is used, the phosphor must avoid excessive overlap with the blue

emission while providing efficient yellow, green and red conversion. This simple compatibility criterion immediately eliminates many phosphors that show attractive photoluminescence under laboratory excitation wavelengths that are not commercially relevant.

Host-lattice engineering can then be used to create suitable sites and suppress non-radiative losses. Aliovalent substitution and charge compensation may stabilize dopant incorporation, while isovalent substitution can adjust local symmetry and activator separation. Co-doping can be used for sensitization, color balancing or energy-transfer cascades, but it should be introduced only when the energy-level diagram supports a plausible transfer route. Defect engineering provides another route, as demonstrated by recent Dy/Eu borates in which oxygen-related defects contribute to self-emission and can be modified through synthesis atmosphere [17]. The challenge is to distinguish beneficial defects from uncontrolled quenching centers.

Thermal stability should also be treated as a design variable from the beginning. A rigid lattice with a suitable band gap, low electron–phonon coupling and well-confined activator sites can reduce thermal quenching, but excessive lattice rigidity does not necessarily maximize absorption or transfer. The optimum host is therefore a compromise among excitation strength, radiative probability, phonon coupling, activator solubility and thermal expansion. This trade-off explains why a single numerical metric such as quantum yield cannot be used as the sole screening criterion.

Sustainable synthesis is another emerging consideration. Conventional high-temperature routes remain useful, but lower-temperature combustion, sol–gel, hydrothermal, microwave and flux-assisted approaches may reduce processing time and energy use. Their adoption should nevertheless be accompanied by rigorous phase and impurity analysis. A low-energy synthesis route that produces variable phase composition is unlikely to provide a reproducible material platform.

7. Scientific and practical significance

The significance of RE-activated borate phosphors lies in the possibility of connecting detailed solid-state chemistry with a technologically measurable lighting function. At the fundamental level, these materials provide a useful platform for studying how coordination geometry, symmetry, lattice dynamics and defects control electronic transitions and energy migration. At the materials level, they allow the spectral output to be engineered through host substitution, activator concentration and co-doping. At the device level, successful integration could improve the balance between efficiency, thermal reliability and color quality in pc-wLEDs.

The most promising direction is not necessarily the search for a universally optimal borate composition. Instead, progress is likely to come from establishing transferable design rules: which host motifs stabilize particular RE sites; which donor–acceptor pairs provide efficient transfer under practical excitation wavelengths; which structural features suppress concentration and thermal quenching; and which combinations produce stable chromaticity under realistic operating temperatures. Recent examples of high quantum efficiency, energy-transfer-controlled color tuning and thermally stable single-component emission indicate that such design principles are becoming experimentally accessible [12,18–22].

8. Conclusions

RE-activated borate phosphors have emerged as versatile spectral-conversion materials for w-LEDs, benefiting from the structural diversity of BO_3/BO_4 units and tunable rare-earth environments. Recent advances demonstrate that activator concentration, defects, crystal symmetry, and energy-transfer pathways can be jointly exploited to control emission color and thermal stability. However, predictive structure–luminescence relationships and reliable translation from powder properties to practical LED performance remain insufficiently established. Future research should therefore integrate crystallographic, spectroscopic, thermal, and device-level studies, with greater emphasis on excitation compatibility, reproducible synthesis, long-term stability, and standardized evaluation under realistic operating conditions. Overall, RE-activated borates offer a promising platform for next-generation w-LED phosphors when crystal chemistry, photophysics, and device requirements are considered collectively.

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