



Role of Borate Host Materials in Persistent Luminescence: Fundamentals, Materials, and Outdoor Applications

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Abstract

Persistent luminescence has attracted considerable attention because of its ability to emit light for extended periods after the removal of the excitation source, making it highly suitable for energy-efficient and self-sustaining lighting technologies. Among various host materials, borate compounds have emerged as promising candidates owing to their excellent chemical stability, structural diversity, optical transparency, and ability to accommodate a wide range of rare-earth activators. This theoretical review discusses the fundamental principles of persistent luminescence with particular emphasis on the role of borate host materials in governing charge trapping, defect formation, and radiative recombination. The influence of crystal structure, host–activator interactions, and defect engineering on afterglow performance is critically examined. Recent developments in borate-based persistent phosphors for outdoor applications, including emergency lighting, road safety systems, pathway illumination, and public infrastructure, are also summarized. Furthermore, current challenges related to trap optimization, luminescence efficiency, environmental stability, and long-term performance are discussed, together with future research perspectives. This review provides a comprehensive understanding of borate host materials and highlights their potential for the development of advanced persistent phosphors for sustainable outdoor lighting applications.

Keywords: *Persistent luminescence, Borate host materials, Afterglow phosphors, Defect engineering; Charge trapping.*

1. Introduction

Persistent luminescence is a unique optical phenomenon in which a material continues to emit light for an extended period after the external excitation source has been removed. Unlike conventional photoluminescence, where light emission ceases immediately after excitation, persistent phosphors are capable of storing excitation energy within crystal defects and gradually releasing it through delayed radiative recombination. This prolonged afterglow has attracted considerable scientific and technological interest because it enables illumination without continuous electrical power or external light sources [1,2].



The performance of persistent phosphors is governed by three key components: the host lattice, activator ions, and defect-related trapping centers. Among these, the host material provides the structural framework that determines crystal stability, defect formation, charge transport, and energy transfer processes. Consequently, the selection of an appropriate host lattice is fundamental for achieving high afterglow intensity, prolonged emission duration, and good environmental stability. Different host materials create distinct crystal fields and defect environments, which directly influence the trapping and release of charge carriers responsible for persistent luminescence [8,17].

Borate compounds have emerged as attractive host materials owing to their excellent chemical stability, high optical transparency, relatively low phonon energy, and remarkable structural diversity. The boron–oxygen framework, composed of BO_3 triangles and BO_4 tetrahedra, forms a wide variety of crystal structures capable of accommodating rare-earth activator ions without significantly disturbing the crystal lattice. This structural flexibility facilitates the formation of suitable trapping centers while maintaining efficient luminescence, making borate hosts promising candidates for persistent phosphor applications [11–16].

Rare-earth ions such as Eu^{2+} , Ce^{3+} , Tb^{3+} , and Dy^{3+} are commonly introduced into borate hosts to generate luminescent centers and optimize charge trapping. In many systems, Eu^{2+} functions as the principal emission center, whereas co-dopants such as Dy^{3+} create additional trapping sites that prolong the afterglow. The interaction between the borate host lattice, activator ions, and crystal defects determines the overall luminescence efficiency, emphasizing the importance of host-dependent defect engineering in persistent phosphors [9,15,18].

The increasing demand for sustainable and energy-efficient lighting technologies has stimulated extensive research on persistent phosphors for outdoor applications. Unlike conventional lighting systems, persistent phosphors can be excited by sunlight or ultraviolet radiation and subsequently emit visible light for several hours without additional energy input. These characteristics make them attractive for emergency lighting, road and traffic safety signs, pathway illumination, public infrastructure, landscape lighting, and other outdoor environments where reliable illumination is required during power interruptions or low-light conditions [2,27,35].

Although numerous studies have reported the synthesis and luminescence properties of borate phosphors, comprehensive discussions focusing specifically on the role of borate host materials remain relatively limited. Most investigations emphasize activator ions, defect engineering, or synthesis methods, while the influence of the host lattice on persistent



luminescence is often discussed only briefly. A systematic theoretical understanding of how borate hosts affect charge trapping, carrier transport, and afterglow behavior is therefore essential for the rational design of high-performance persistent phosphors [27,29,34].

This review presents a comprehensive theoretical discussion of borate host materials in persistent luminescence. It first summarizes the fundamental mechanisms governing persistent luminescence, followed by an analysis of the structural characteristics of borate hosts, the role of rare-earth activators and defect engineering, and the influence of host materials on optical performance. Finally, recent progress in outdoor applications and future research opportunities are discussed to provide a scientific framework for the development of advanced borate-based persistent phosphors [2,27].

2. Fundamentals of Persistent Luminescence

Persistent luminescence is a delayed light-emission phenomenon in which a phosphor continues to emit visible or near-infrared radiation after the excitation source has been removed. Unlike conventional fluorescence, persistent luminescence involves the temporary storage of excitation energy within crystal defects or trapping centers, followed by its gradual release through thermally assisted charge carrier recombination. Consequently, the intensity and duration of the afterglow depend on the efficiency of charge trapping, storage, migration, and recombination processes [1,2].

The persistent luminescence process generally begins with the absorption of excitation energy from ultraviolet light, visible light, X-rays, or sunlight. Excited electrons are promoted to higher-energy states or the conduction band, where a fraction of the charge carriers becomes trapped by intrinsic or extrinsic defects within the host lattice instead of recombining immediately. These trapped carriers remain stored until sufficient thermal energy releases them, allowing delayed recombination at luminescent centers and producing persistent emission [2,8].

The host lattice plays a crucial role in determining persistent luminescence because it governs the formation, distribution, and stability of trapping centers. Crystal defects such as vacancies, interstitials, antisite defects, and impurity-related defects introduce localized energy levels within the band gap that serve as electron or hole traps. The depth of these traps strongly influences afterglow behavior: shallow traps release charge carriers rapidly, whereas excessively deep traps hinder carrier release at room temperature. Therefore, an appropriate trap depth is essential for achieving intense and long-lasting luminescence [8,17].



Rare-earth ions act as luminescence centers by providing discrete electronic energy levels responsible for characteristic emissions. Among them, Eu^{2+} is the most widely employed activator because of its efficient $4f^65d^1 \rightarrow 4f^7$ transition, while ions such as Ce^{3+} , Tb^{3+} , Dy^{3+} , and Eu^{3+} are frequently used either as activators or co-dopants. In many persistent phosphors, co-dopants promote the formation of trapping centers, thereby enhancing charge storage and extending the afterglow duration [9,18,19].

Thermoluminescence (TL) analysis has become one of the most effective techniques for investigating persistent luminescence because it provides valuable information about trap depth, trap density, and charge release kinetics. The characteristics of TL glow curves are closely related to afterglow performance, enabling the optimization of defect structures for improved luminescence efficiency [14,17].

Overall, persistent luminescence results from the synergistic interaction between the host lattice, defect structure, trapping centers, and activator ions. A comprehensive understanding of these fundamental mechanisms provides the scientific basis for designing advanced borate-based persistent phosphors with improved optical performance and long-duration afterglow for practical outdoor applications [2,8].

3. Borate Host Materials for Persistent Luminescence

Borate compounds have attracted considerable attention as host materials for persistent phosphors because of their excellent chemical stability, wide optical transparency, low phonon energy, and exceptional structural versatility. Unlike many conventional oxide hosts, borates exhibit a rich variety of crystal structures originating from the diverse coordination environments of boron atoms. This structural diversity provides favorable conditions for incorporating rare-earth activator ions and engineering defect centers that are essential for persistent luminescence [9,11].

The fundamental structural units of borate materials consist of planar BO_3 triangles and tetrahedral BO_4 units. These building blocks can polymerize in numerous ways to form isolated groups, one-dimensional chains, two-dimensional layers, or three-dimensional frameworks. Consequently, borate compounds exhibit remarkable flexibility in crystal chemistry, enabling the formation of stable host lattices with different coordination environments for luminescent ions [10,12].

The crystal structure of the host lattice significantly influences the optical behavior of persistent phosphors. Parameters such as lattice symmetry, bond length, coordination geometry, and local crystal field determine the distribution of activator ions and the formation of intrinsic



defects. Since the electronic environment surrounding rare-earth ions depends strongly on the host structure, variations in borate crystal chemistry directly affect excitation spectra, emission intensity, trap distribution, and afterglow duration [12,20].

An important advantage of borate hosts is their ability to accommodate a wide range of rare-earth ions without causing severe lattice distortion. The relatively open crystal frameworks of many borates facilitate the substitution of host cations by activator ions such as Eu^{2+} , Eu^{3+} , Ce^{3+} , Tb^{3+} , Sm^{3+} , and Dy^{3+} . Such substitutions promote efficient energy transfer while simultaneously creating defect sites that participate in charge trapping and release processes [11,13].

Several borate systems have been investigated as promising luminescent hosts, including $\text{Na}_3\text{La}_2(\text{BO}_3)_3$, $\text{NaSr}_4(\text{BO}_3)_3$, $\text{LiSr}_4(\text{BO}_3)_3$, and related mixed-alkaline-earth borates. These materials exhibit favorable structural stability together with efficient rare-earth activation, making them attractive candidates for ultraviolet-excited phosphors and long-afterglow materials. Their structural characteristics also permit compositional modifications through suitable dopants and co-dopants to optimize luminescence performance [9,13–16].

Recent studies have further demonstrated that the structural flexibility of borate materials provides opportunities for tailoring defect chemistry, improving charge carrier mobility, and enhancing persistent luminescence. Rational control of crystal structure and local coordination environments therefore represents an effective strategy for developing high-performance borate-based phosphors for next-generation outdoor lighting and related optical applications [27,30].

Overall, the structural diversity of borate hosts offers considerable opportunities for designing persistent phosphors with tailored optical properties. Variations in crystal symmetry, local coordination, and defect chemistry provide effective routes for controlling charge trapping, carrier transport, and energy transfer, thereby enabling the optimization of luminescence efficiency and afterglow performance. Consequently, the selection of an appropriate borate host significantly influences the optical properties and overall efficiency of persistent phosphors [11–16,20,21].

Therefore, the host material is not merely a structural support but an active component controlling persistent luminescence. A thorough understanding of borate crystal chemistry is essential for developing next-generation persistent phosphors with enhanced afterglow characteristics, improved thermal stability, and superior environmental durability [11–16,20,21].



4. Rare-Earth Activators and Defect Engineering

Rare-earth activator ions play a crucial role in determining the optical performance of persistent phosphors. While the host lattice provides the structural framework for energy storage, activator ions function as luminescent centers where radiative recombination occurs. The interaction between activator ions, crystal defects, and the borate host lattice governs the efficiency, emission wavelength, and afterglow duration of persistent luminescence. Consequently, careful selection of activator ions and defect engineering strategies is essential for designing high-performance borate-based persistent phosphors [1,2,23].

Among the various activators, europium has been the most extensively investigated because of its favorable electronic configuration and high luminescence efficiency. In many persistent phosphors, Eu^{2+} acts as the primary emission center, producing broad-band emission through the allowed $4f^65d^1 \rightarrow 4f^7$ electronic transition. The emission wavelength depends strongly on the crystal field provided by the host lattice, allowing different borate hosts to generate blue, green, or yellow luminescence. This host-dependent behavior demonstrates the important influence of the borate crystal environment on the optical properties of Eu^{2+} -activated phosphors [15,21,24].

Co-doping with rare-earth ions such as Dy^{3+} has proven to be an effective approach for improving persistent luminescence. Unlike Eu^{2+} , which primarily serves as the emission center, Dy^{3+} generally acts as a trap-forming ion that enhances charge storage within the crystal lattice. The additional defect levels introduced by Dy^{3+} increase the number of available trapping centers, allowing excited electrons to remain stored for longer periods before thermal release. This cooperative interaction between Eu^{2+} and Dy^{3+} significantly improves afterglow intensity and emission duration in many borate phosphors [9,15,23,24].

Cerium and terbium have also been widely explored as activator ions in borate host materials. Ce^{3+} exhibits efficient ultraviolet absorption and fast luminescence, making it useful for ultraviolet-excited phosphors and energy transfer processes. Terbium, on the other hand, is well known for its characteristic green emission resulting from $4f-4f$ electronic transitions. Depending on the host composition and local crystal environment, Ce^{3+} and Tb^{3+} can either function as independent luminescent centers or participate in energy transfer processes that modify emission characteristics and improve optical performance [11,20,26].

An equally important aspect of persistent luminescence is defect engineering. Crystal defects create localized energy levels within the forbidden band gap that function as electron or hole traps. These defects may originate naturally during crystal growth or be intentionally



introduced through aliovalent doping, co-doping, or controlled synthesis conditions. The concentration, distribution, and energy depth of these trapping centers determine the efficiency of charge storage and delayed recombination, thereby directly influencing afterglow brightness and persistence [2,9,23].

Trap depth is a key parameter in defect engineering. Shallow traps release charge carriers rapidly, producing high initial brightness but relatively short afterglow duration. Conversely, excessively deep traps retain carriers too strongly, limiting their release under ambient conditions and reducing luminescence efficiency. Therefore, persistent phosphors containing an appropriate distribution of shallow and deep traps generally exhibit superior optical performance. Optimization of trap depth through suitable activator selection, co-doping, and host modification has become one of the principal strategies for improving borate-based persistent phosphors [2,9].

The interaction between the borate host lattice and activator ions further influences defect formation and carrier transport. Variations in crystal symmetry, lattice distortion, and local coordination alter the energy levels of trapping centers and modify the probability of radiative recombination. As a result, the same activator ion may exhibit significantly different persistent luminescence behavior when incorporated into different borate hosts. Understanding this host–activator relationship is therefore essential for the rational design of efficient persistent phosphors with enhanced afterglow properties [11–16,20,21].

Overall, the performance of borate-based persistent phosphors is governed by the combined effects of rare-earth activators and defect engineering. Appropriate selection of activator ions together with precise control of crystal defects enables optimization of charge trapping, carrier transport, and radiative recombination. Continued research on host–activator interactions and defect-controlled luminescence is expected to contribute significantly to the development of advanced persistent phosphors for outdoor lighting and related optical applications [27,29,34].

5. Outdoor Applications of Borate-Based Persistent Phosphors

Persistent phosphors have emerged as promising materials for outdoor lighting because they can store excitation energy from natural sunlight or artificial ultraviolet radiation and subsequently emit visible light for extended periods without continuous electrical power. This unique property offers significant advantages for sustainable illumination, particularly in locations where uninterrupted electrical supply is unavailable or energy conservation is a



priority. The excellent chemical stability and optical transparency of borate host materials further enhance their suitability for long-term outdoor operation [2,27].

One of the most important applications of borate-based persistent phosphors is emergency and safety lighting. Persistent phosphors can provide illumination immediately after power failure without requiring external electrical input, making them suitable for emergency exit signs, evacuation pathways, tunnels, underground facilities, and public buildings. Their long afterglow improves visibility during critical situations while reducing maintenance requirements and operating costs [13,27].

Borate phosphors also show considerable potential for traffic and transportation safety systems. Long-lasting afterglow materials can be incorporated into road markings, traffic signs, pedestrian crossings, bicycle paths, and highway guidance systems, where stored solar energy provides nighttime visibility. Compared with conventional reflective materials, persistent phosphors remain visible even in the absence of vehicle headlights, thereby improving road safety under low-light conditions [25,35].

The high environmental stability of borate hosts makes them attractive for landscape and architectural lighting. Persistent phosphors can be incorporated into decorative paving blocks, garden pathways, building facades, parks, monuments, and recreational areas to provide aesthetically pleasing nighttime illumination while minimizing electricity consumption. Their resistance to moisture, thermal fluctuations, and chemical degradation contributes to reliable outdoor performance over extended service periods [29,33].

Recent developments in borate-based phosphors have also expanded their applications beyond conventional lighting. Advanced persistent luminescent materials are being explored for anti-counterfeiting technologies, optical information storage, smart safety labels, and multifunctional luminescent coatings. These emerging applications take advantage of controlled afterglow behavior, tunable emission colors, and improved material durability achieved through host engineering and defect optimization [34,35].

Despite these promising applications, several challenges remain before borate-based persistent phosphors can achieve widespread commercial implementation. Improving afterglow brightness under natural sunlight excitation, enhancing long-term environmental stability, and optimizing trap distribution for prolonged emission remain active areas of research. Continued advances in borate host design, defect engineering, and rare-earth activation are expected to further expand the use of persistent phosphors in sustainable outdoor lighting and next-generation smart infrastructure [28,34].



6. Challenges and Future Perspectives

Despite significant progress in persistent luminescence research, borate-based phosphors still face several scientific and technological challenges that limit their widespread practical application. One of the primary concerns is achieving high afterglow intensity under low-energy excitation sources such as natural sunlight or indoor lighting. Many existing borate phosphors require ultraviolet excitation, which restricts their efficiency in real outdoor environments where the ultraviolet component of sunlight is relatively limited [27,34].

Another important challenge is the precise control of defect structures within borate host lattices. Persistent luminescence strongly depends on the concentration, distribution, and energy depth of trapping centers. However, defect formation is highly sensitive to synthesis conditions, chemical composition, and rare-earth doping concentration. Developing reliable defect-engineering strategies capable of producing reproducible trap distributions remains an important research objective [8,18].

Improving the environmental durability of borate phosphors is also essential for long-term outdoor applications. Although many borate hosts exhibit good chemical stability, prolonged exposure to moisture, temperature fluctuations, and atmospheric conditions may gradually reduce luminescence performance. Therefore, improving weather resistance through compositional optimization, protective coatings, and host modification represents an important direction for future research [29,33].

Recent advances in materials engineering have demonstrated that co-doping strategies, compositional tuning, and rational host design can effectively improve trap characteristics, energy transfer efficiency, and emission stability. In addition, computational methods such as first-principles calculations and defect modeling are increasingly being employed to predict trap formation and guide the design of high-performance persistent phosphors before experimental synthesis, thereby accelerating materials discovery [27,31,34].

Future research is also expected to explore multifunctional borate phosphors with tunable emission colors, broadband excitation, improved sunlight charging capability, and enhanced long-term stability. Such developments could significantly expand applications in smart cities, emergency infrastructure, optical information storage, anti-counterfeiting technologies, environmental sensing, and sustainable outdoor lighting systems. Continued collaboration between crystal chemistry, defect physics, computational materials science, and optical engineering will play a crucial role in advancing the next generation of borate-based persistent luminescent materials [27,34,35].



7. Conclusion

Borate host materials have emerged as an important class of inorganic phosphors for persistent luminescence because of their excellent structural flexibility, chemical stability, and favorable optical properties. Their ability to accommodate various rare-earth activator ions while supporting efficient defect formation makes them highly suitable for long-lasting afterglow applications. The persistent luminescence performance of borate phosphors is governed by the combined influence of the host lattice, crystal defects, trapping centers, and activator ions, emphasizing the importance of host-dependent defect engineering. Recent advances in material design and synthesis have significantly improved the optical performance of borate-based persistent phosphors, expanding their potential for sustainable outdoor lighting, public safety systems, and energy-efficient illumination. Nevertheless, further improvements in emission brightness, trap optimization, environmental durability, and long-term stability remain necessary for large-scale practical implementation. Continued research on novel borate host materials, advanced characterization techniques, and theoretical modeling is expected to provide deeper insight into persistent luminescence mechanisms and accelerate the development of next-generation afterglow phosphors for future outdoor applications.

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