



Borate Phosphors for Optical Thermometry: A Theoretical Review of Mechanisms and Applications

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Abstract

Optical thermometry has emerged as an effective non-contact temperature sensing technique owing to its high sensitivity, rapid response, and immunity to electromagnetic interference. Among various luminescent materials, borate phosphors have attracted significant attention because of their excellent chemical and thermal stability, low phonon energy, structural diversity, and favorable crystal-field environments for rare-earth activators. This review presents a theoretical overview of borate phosphors for optical thermometry, focusing on the relationship between host lattice structure, luminescence mechanisms, and temperature-sensing performance. The fundamental principles of fluorescence intensity ratio (FIR) thermometry, including thermally coupled and non-thermally coupled emission mechanisms. These are discussed together with the influence of host materials, rare-earth activators, crystal-field effects, electron-phonon interactions, and defect engineering. Recent advances reported are summarized, highlighting host-lattice engineering, alkali-ion co-doping, and dual-emission strategies for improving thermometric sensitivity. Finally, current challenges and future research directions are discussed. This review provides a theoretical framework for the design and development of high-performance borate-based optical thermometric materials.

Keywords: Optical thermometry, Fluorescence intensity ratio (FIR), Rare-earth ions, Luminescence, Crystal-field engineering, Temperature sensing.

1. Introduction

Temperature is one of the most important physical parameters governing physical, chemical, and biological processes. Accurate temperature measurement is essential in numerous fields, including industrial manufacturing, energy conversion, environmental monitoring, aerospace engineering, microelectronics, and biomedical diagnostics. Conventional temperature sensors, such as thermocouples, resistance temperature detectors, and infrared pyrometers, are widely used because of their simplicity and reliability. However, these techniques often suffer from limitations including physical contact requirements, susceptibility to electromagnetic interference, limited spatial resolution, and reduced accuracy in harsh or inaccessible environments. These challenges have stimulated increasing interest in optical temperature sensing technologies that enable rapid, remote, and non-invasive measurements [2–6].



Among various optical sensing approaches, luminescence-based optical thermometry has emerged as one of the most promising techniques due to its high sensitivity, fast response, and immunity to electromagnetic noise. In particular, the fluorescence intensity ratio (FIR) technique has received considerable attention because it is a self-referencing method that minimizes errors caused by fluctuations in excitation intensity, detector efficiency, and phosphor concentration. Depending on the emission mechanism, FIR thermometry can be achieved using either thermally coupled energy levels (TCLs) or non-thermally coupled luminescent centers exhibiting distinct temperature-dependent emission behaviors [3–6].

The performance of an optical thermometer depends strongly on the host lattice. An ideal host material should possess excellent chemical and thermal stability, high optical transparency, low phonon energy, and a crystal structure capable of accommodating luminescent ions without significant lattice distortion. Among various inorganic hosts, including oxides, fluorides, phosphates, silicates, aluminates, and borates, borate compounds have attracted increasing attention because of their remarkable structural flexibility and favorable optical properties [2,7–10].

Borate phosphors are constructed from triangular BO_3 and tetrahedral BO_4 structural units that form diverse crystal frameworks capable of accommodating various rare-earth activators. In addition to their structural diversity, borate hosts generally exhibit wide optical transparency, relatively low phonon energies, good chemical and thermal stability, and excellent resistance to environmental degradation. These characteristics show non-radiative relaxation and contribute to stable temperature-dependent luminescence and making borate phosphors attractive host materials for optical thermometry [7–10].

The temperature-sensing performance of borate phosphors is further governed by the choice of activator ions. Rare-earth ions such as Tb^{3+} , Dy^{3+} , Eu^{2+} , Sm^{2+} , and Ce^{3+} exhibit characteristic temperature-dependent emissions that are influenced by crystal-field interactions, electron-phonon coupling, energy transfer processes, and the local coordination environment of the host lattice. Recent advances in host-lattice engineering, alkali-ion co-doping, defect modulation, and dual-emission strategies have significantly improved fluorescence intensity ratio sensitivity and thermal stability, expanding the application of borate phosphors in industrial monitoring, biomedical diagnostics, environmental sensing, and photonic devices [7–10].

Although numerous studies have reported the synthesis and experimental performance of borate-based optical thermometers, comprehensive theoretical discussions linking borate crystal chemistry with luminescence mechanisms and thermometric behavior remain limited. This review therefore provides a concise theoretical overview of borate phosphors for optical thermometry by discussing the fundamental principles of fluorescence intensity ratio thermometry, the structural characteristics of borate host materials, the role of rare-earth activators, recent advances reported up to 2024, and future research directions for the rational design of high-performance optical thermometric materials.



2. Fundamentals of Optical Thermometry

Optical thermometry is a non-contact temperature sensing technique that utilizes temperature-dependent changes in the luminescence properties of phosphor materials. Unlike conventional contact-based thermometers, it enables remote temperature measurement with high spatial resolution, rapid response, and immunity to electromagnetic interference. These advantages make optical thermometry particularly attractive for applications in microelectronics, biomedical diagnostics, optical fiber sensors, and harsh industrial environments where conventional temperature sensors are difficult to employ [3–6].

Among the various luminescence-based methods, the fluorescence intensity ratio (FIR) technique is the most widely used because of its self-referencing nature. Instead of relying on the absolute intensity of a single emission band, the fluorescence intensity ratio (FIR) technique determines temperature from the ratio of two temperature-dependent emission intensities, thereby reducing errors associated with fluctuations in excitation intensity, detector sensitivity, and phosphor concentration. For thermally coupled levels (TCLs), the FIR follows a Boltzmann-type relationship with temperature [14]. The fluorescence intensity ratio follows the Boltzmann relationship:

$$FIR = \frac{I_1}{I_2} = A \exp\left(-\frac{\Delta E}{k_B T}\right) \quad (1)$$

where I_1 and I_2 are the emission intensities, A is a constant related to transition probabilities, ΔE is the energy separation between the emitting states, K_B is the Boltzmann constant, and T is the absolute temperature [3–5].

Based on the origin of the emission transitions, FIR thermometers are generally classified into thermally coupled level (TCL) and non-thermally coupled level (non-TCL) systems. In TCL thermometry, two closely spaced excited states remain in thermal equilibrium, allowing the emission intensity ratio to follow the Boltzmann distribution. Rare-earth ions such as Er^{3+} , Ho^{3+} , and Nd^{3+} have been investigated for TCL-based optical thermometry because some of their excited-state manifolds exhibit energy separations suitable for temperature-dependent thermal population redistribution [3–6]. In contrast, non-TCL thermometers utilize emissions originating from independent energy levels or different luminescent centers. Their temperature dependence arises from differences in thermal quenching, radiative transition probabilities, electron-phonon interactions, or energy transfer processes rather than thermal equilibrium. Consequently, non-TCL systems often exhibit greater flexibility in material design and can achieve higher thermometric sensitivity than conventional TCL-based phosphors [12–16]. Recent dual-emission systems, particularly those involving $\text{Eu}^{2+}/\text{Sm}^{2+}$, $\text{Tb}^{3+}/\text{Eu}^{3+}$, and $\text{Bi}^{3+}/\text{Eu}^{3+}$, have demonstrated remarkable improvements in temperature-sensing performance [6–10].

The performance of an optical thermometer is commonly evaluated using its relative sensitivity, together with its operating temperature range, thermal



stability, repeatability, and long-term reliability. These characteristics are strongly influenced by the host lattice through crystal-field strength, phonon energy, lattice symmetry, and defect distribution, which collectively govern radiative and non-radiative relaxation processes. Therefore, the rational design of efficient optical thermometers requires simultaneous optimization of both the activator ions and the host material. Owing to their structural flexibility, low phonon energy, and excellent chemical stability, borate phosphors provide an attractive platform for achieving high-performance luminescent thermometry [7–10].

3. Borate Host Materials for Optical Thermometry

The host lattice plays a fundamental role in determining the luminescence efficiency and thermometric performance of phosphor materials. Although rare-earth ions act as the luminescent centers, their optical behavior is strongly influenced by the structural and chemical characteristics of the surrounding host matrix. Crystal symmetry, local coordination environment, phonon energy, lattice defects, and chemical stability collectively govern radiative transition probabilities, non-radiative relaxation, and thermal quenching processes. Therefore, selecting an appropriate host material is essential for achieving high sensitivity and stable optical thermometry [2,7–10].

Among various inorganic host materials, borate compounds have attracted considerable attention because of their unique crystal chemistry and favorable optical properties. Borate structures are primarily constructed from planar BO_3 triangles and tetrahedral BO_4 units, which combine in different proportions to produce a wide variety of crystalline frameworks. This structural diversity provides multiple crystallographic sites for incorporating rare-earth activators while maintaining excellent structural stability. Consequently, borate hosts offer remarkable flexibility for tailoring the local crystal-field environment and optimizing luminescence characteristics [7–10].

Another important advantage of borate phosphors is their relatively low effective phonon energy compared with many conventional oxide hosts. Lower phonon energies suppress multiphonon non-radiative relaxation, thereby improving radiative emission efficiency and reducing thermal quenching. In addition, borate materials generally exhibit high optical transparency in the ultraviolet and visible regions, good chemical durability, excellent thermal stability, and relatively low synthesis temperatures [26,27,28]. These characteristics enable stable luminescence over a broad temperature range, making borate compounds attractive candidates for optical thermometry [7–11].

The crystal structure of borate hosts also strongly influences the local environment surrounding activator ions. Variations in coordination geometry, bond length, and lattice symmetry modify crystal-field strength and Stark splitting of rare-earth energy levels, leading to changes in emission wavelength, transition probability, and fluorescence intensity ratio. As a result, the same activator ion may exhibit significantly different thermometric behavior in different borate hosts. This strong host-activator interaction highlights the importance of crystal engineering in the development of high-performance optical thermometers [8–11].



Borate compounds further provide excellent compositional flexibility through the incorporation of alkali, alkaline-earth, and rare-earth ions. Chemical substitution or alkali-ion co-doping can modify lattice distortion, crystal-field symmetry, and electron-phonon coupling, allowing systematic tuning of luminescence properties and temperature sensitivity [29]. Such host-lattice engineering has become an effective strategy for improving the performance of borate-based optical thermometers without altering the principal luminescent activator [8–10]. Several borate families, including potassium, lithium, strontium, barium, and rare-earth borates, have demonstrated promising thermometric properties after rare-earth activation. Their wide structural diversity enables optimization of emission characteristics, thermal stability, and operating temperature range according to specific sensing requirements. Owing to this unique combination of structural flexibility, low phonon energy, chemical stability, and favorable optical properties, borate phosphors have emerged as one of the most promising host materials for next-generation optical thermometry [7–10].

4. Rare-Earth Activators and Luminescence Mechanisms in Borate Phosphors

The luminescence performance of borate phosphors is primarily governed by the electronic structure of the incorporated activator ions. While the borate host lattice provides structural stability and an appropriate crystal-field environment, rare-earth ions serve as luminescent centers responsible for temperature-dependent emission. Their partially filled 4f orbitals are effectively shielded by the outer 5s² and 5p⁶ shells, resulting in narrow emission bands, high chemical stability, and excellent spectral reproducibility. Nevertheless, the surrounding crystal environment significantly influences Stark splitting, radiative transition probabilities, electron-phonon coupling, and non-radiative relaxation processes, thereby determining the thermometric performance of the phosphor [3,7–10].

Among the various activator ions, Er³⁺ has been the most extensively investigated for fluorescence intensity ratio (FIR)-based optical thermometry because of the presence of two closely spaced thermally coupled excited states, ²H_{11/2} and ⁴S_{3/2}. These energy levels remain in thermal equilibrium over a wide temperature range and obey the Boltzmann distribution. Upon excitation, thermal population redistribution between these levels results in opposite variations of the corresponding green emissions, enabling accurate temperature determination through the fluorescence intensity ratio. Owing to its predictable luminescence behavior and good reproducibility, Er³⁺ remains the benchmark activator for conventional FIR thermometry [3–6,24].

Unlike Er³⁺, Tb³⁺ exhibits an alternative thermometric mechanism based primarily on temperature-dependent radiative branching and electron-phonon interactions. The characteristic green emission originating from the ⁵D₄ → ⁷F₅ transition gradually decreases with increasing temperature because of thermal quenching, whereas weaker emission bands may increase owing to phonon-assisted population redistribution and local symmetry relaxation. This unusual thermal behavior allows FIR measurements without relying exclusively on thermally coupled energy levels and has attracted considerable attention in



recently developed borate phosphors, particularly potassium tetraborate systems [8–10,17,23].

Dy³⁺ is another important activator for non-contact optical thermometry because its blue ($^4F_{9/2} \rightarrow ^6H_{15/2}$) and yellow ($^4F_{9/2} \rightarrow ^6H_{13/2}$) emissions exhibit different thermal responses. Since these transitions are not thermally coupled, the fluorescence intensity ratio is mainly governed by differences in thermal quenching and local crystal-field interactions rather than Boltzmann population redistribution. Dy³⁺-activated borate phosphors therefore provide an attractive alternative for non-TCL thermometry, offering broad operating temperature ranges and stable emission characteristics [6–10].

Recent studies have also demonstrated the advantages of dual-emission systems, where two independent luminescent centers produce emissions with different temperature dependences. Among these, Eu²⁺/Sm²⁺ co-activated borate phosphors have attracted significant attention because the broad 5d–4f emission of Eu²⁺ and the characteristic 4f–4f emission of Sm²⁺ respond differently to increasing temperature. The resulting fluorescence intensity ratio exhibits exceptionally high sensitivity compared with conventional thermally coupled systems. Similar improvements have been reported in Tb³⁺/Eu³⁺ and Bi³⁺/Eu³⁺ co-doped borate phosphors, demonstrating that multi-center luminescence provides an effective strategy for enhancing optical thermometric performance [6,8–10].

The optical behavior of these activator ions is strongly influenced by the crystal-field environment of the borate host. Variations in lattice symmetry, coordination geometry, and bond lengths modify Stark splitting, transition probabilities, and branching ratios of the rare-earth energy levels. Consequently, identical activator ions may exhibit markedly different emission characteristics when incorporated into different borate structures. This strong dependence of luminescence on host composition has made host-lattice engineering one of the most important approaches for optimizing optical thermometers [7–10].

In addition to host selection, alkali-ion co-doping has emerged as an effective method for improving luminescence performance. The incorporation of Li⁺ or Na⁺ ions introduces slight lattice distortions that modify local symmetry and crystal-field strength surrounding the activator ions [22]. These structural changes influence electron-phonon coupling, suppress non-radiative relaxation, and regulate radiative branching probabilities, leading to enhanced emission intensity, improved thermal stability, and higher thermometric sensitivity. Such crystal-field engineering strategies have become increasingly important in recent borate-based optical thermometers [8–10].

A theoretical understanding of these luminescence processes is commonly obtained using Judd–Ofelt (J–O) theory, which correlates optical transition probabilities with the local structural environment of rare-earth ions. The intensity parameters Ω_2 , Ω_4 , and Ω_6 provide valuable information regarding local symmetry, covalency, and lattice rigidity. Among them, Ω_2 is particularly sensitive to local structural distortion, whereas Ω_4 and Ω_6 mainly reflect bulk crystal characteristics. Changes in these parameters caused by chemical substitution or



co-doping directly influence radiative transition probabilities and fluorescence efficiency, making Judd–Ofelt analysis an important theoretical tool for interpreting the optical behavior of borate phosphors [8–10].

Overall, the thermometric performance of borate phosphors results from the combined influence of activator electronic structure, host-lattice characteristics, crystal-field interactions, electron-phonon coupling, and defect chemistry. Rational optimization of these factors through appropriate activator selection and crystal engineering has enabled substantial improvements in fluorescence intensity ratio sensitivity and thermal stability. These advances provide the scientific basis for the development of highly efficient borate-based optical thermometers for future industrial, environmental, and biomedical applications.

5. Recent Advances in Borate-Based Optical Thermometry

Recent research has significantly advanced the development of borate phosphors for optical thermometry through improved host-lattice engineering, activator optimization, and dual-emission strategies. Rather than focusing solely on increasing luminescence intensity, current studies aim to enhance fluorescence intensity ratio (FIR) sensitivity, widen the operating temperature range, suppress thermal quenching, and improve long-term stability. These developments have established borate phosphors as promising materials for high-performance non-contact temperature sensing in industrial, biomedical, and photonic applications [7–10].

One of the most important recent developments is the investigation of Tb³⁺-activated borate phosphors, particularly potassium tetraborate (K₂B₄O₇). Unlike conventional FIR thermometers that rely exclusively on thermally coupled energy levels, Tb³⁺-activated borate phosphors exhibit temperature-dependent radiative branching. The dominant green emission gradually decreases with increasing temperature because of enhanced non-radiative relaxation, whereas weaker emission bands increase owing to phonon-assisted redistribution and changes in local crystal symmetry. This opposite thermal behavior enables reliable FIR measurements without requiring strict thermal equilibrium between excited states, providing an alternative mechanism for optical thermometry [8–10].

Another major advancement has been the emergence of dual-emission luminescent systems [31]. In these phosphors, two independent emission centers exhibit different thermal responses, resulting in a highly temperature-sensitive fluorescence intensity ratio. Among the reported systems, Eu²⁺/Sm²⁺-activated SrB₄O₇ has attracted considerable attention because of its exceptionally high relative sensitivity, far exceeding that of many conventional thermally coupled systems. Similar improvements have also been reported for Bi³⁺/Eu³⁺ and Tb³⁺/Eu³⁺ co-doped borate phosphors, where temperature-dependent energy transfer and different thermal quenching behaviors provide enhanced sensing performance over broad temperature ranges [6,8–10].

Recent studies have also demonstrated that host-lattice engineering plays a decisive role in improving thermometric performance. Chemical substitution and alkali-ion co-doping with Li⁺ or Na⁺ modify crystal-field strength, lattice



symmetry, and electron–phonon interactions surrounding rare–earth ions. These structural modifications influence radiative branching probabilities, suppress non–radiative relaxation, and improve emission stability. As a result, crystal–field engineering has become an effective strategy for optimizing fluorescence intensity ratio sensitivity without changing the principal activator ion [8–10].

In addition to compositional modification, increasing attention has been devoted to defect engineering. Controlled formation of oxygen vacancies, lattice distortions, and intrinsic defects can regulate charge transfer processes and modify the local crystal environment of activator ions. Appropriate defect concentrations improve emission efficiency and thermal stability, whereas excessive defects promote non–radiative recombination. Therefore, precise control of defect chemistry has become an important aspect of designing highly efficient borate–based optical thermometers [7–10].

Recent investigations have further expanded the application potential of borate phosphors beyond laboratory demonstrations. Their excellent chemical durability, optical transparency, and resistance to thermal degradation make them suitable for temperature monitoring in high–temperature industrial processes, optical devices, microelectronics, environmental sensing, and biomedical diagnostics. The combination of non–contact operation, high spatial resolution, and immunity to electromagnetic interference provides significant advantages over conventional temperature sensing technologies [2,7–10].

Despite these advances, several challenges remain. Thermal quenching at elevated temperatures, limited operating temperature windows for some phosphor systems, and insufficient long–term photostability continue to restrict practical applications. Furthermore, a deeper theoretical understanding of the relationship between crystal structure, crystal–field effects, electron–phonon coupling, and defect chemistry is still required for the rational design of next–generation borate phosphors with higher sensitivity and improved operational stability.

Table 1. Representative borate phosphors for optical thermometry

Host phosphor	Activator (s)	Thermometric mechanism	Temperature range	Key advantage	Ref.
SrB ₄ O ₇	Eu ²⁺ /Sm ²⁺	Dual–emission ratiometric thermometry (non–TCL)	Cryogenic to elevated–temperature range; see original paper	Extremely high relative sensitivity; dual temperature/pressure sensing	[31]
LiY ₆ (BO ₃) ₃ O ₅	Bi ³⁺ /Eu ³⁺	Energy–transfer dual–emission FIR	123–483 K	High energy–transfer efficiency and differentiated thermal quenching	[32]



$\text{YAl}_3(\text{BO}_3)_4$	Cr^{3+}	Luminescence-intensity-ratio thermometry	Approximately -150 to 300°C	Simultaneous optical heating and temperature readout	[33]
$\text{NaSrY}(\text{BO}_3)_2$	Ce^{3+}	Temperature-dependent luminescence / intensity thermometry	293 – 473 K	Simple single-emission temperature sensing with reversible response	[34]
$\text{Ba}_3\text{Y}_2\text{B}_4\text{O}_{12}$	$\text{Yb}^{3+}/\text{Ho}^{3+}$	Upconversion FIR thermometry	Around 300 – 550 K	NIR excitation and maximum relative sensitivity of $1.53\% \text{ K}^{-1}$ at 478 K	[35]

6. Challenges, Future Perspectives, and Conclusions

6.1 Challenges

Despite significant progress, several challenges continue to limit the practical application of borate phosphors for optical thermometry. Thermal quenching at elevated temperatures remains one of the major factors reducing luminescence intensity and measurement accuracy. In addition, many fluorescence intensity ratio (FIR)-based systems operate effectively only within a limited temperature range, restricting their applicability under extreme conditions. Precise control of crystal defects, local crystal-field environments, and activator distribution also remains difficult, often leading to variations in luminescence efficiency and sensing reproducibility. Furthermore, long-term photostability and thermal durability require further improvement for reliable operation in practical industrial and biomedical environments [2,7–10].

6.2 Future Perspectives

Future research should focus on rational host-lattice engineering, controlled defect modulation, and optimized activator selection to improve thermometric sensitivity and thermal stability simultaneously. Dual-emission systems and crystal-field engineering through alkali-ion co-doping are expected to remain important strategies for developing highly sensitive optical thermometers. In addition, integrating experimental investigations with theoretical approaches, including crystal-field calculations, Judd–Ofelt analysis, density functional theory (DFT), and data-driven materials design, will provide deeper insight into luminescence mechanisms and accelerate the discovery of advanced borate phosphors. These developments are expected to expand the application of borate-based optical thermometers in industrial monitoring, microelectronics, environmental sensing, photonic devices, and biomedical diagnostics [7–10].

6.3 Conclusions



Borate phosphors have emerged as promising host materials for optical thermometry owing to their structural diversity, excellent chemical and thermal stability, low phonon energy, and favorable crystal-field environments for rare-earth activators. Recent advances in host-lattice engineering, activator optimization, alkali-ion co-doping, and dual-emission strategies have significantly improved fluorescence intensity ratio sensitivity and operational stability. Although challenges related to thermal quenching, defect control, and operating temperature range remain, continued progress in materials design and theoretical understanding is expected to accelerate the development of highly sensitive and reliable borate-based optical thermometers for future scientific, industrial, and biomedical applications.

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