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Electrical and Luminescent Behavior of Calcium Silicate Doped with Erbium and Terbium Ions

DeepaKumari Dr. Rajesh Mahto2

Research Scholar, Department of Physics, YBN University, Rajaulatu Namkum, Ranchi1

Assistant Professor, Department of Physics, YBN University, Rajaulatu Namkum, Ranchi2

Abstract

Calcium silicate phosphors doped with rare-earth ions exhibit remarkable luminescent and electrical properties for optoelectronic applications. This study investigates the electrical conductivity and photoluminescence characteristics of calcium silicate (Ca_2SiO_4*) doped with erbium (*Er^{3+}*) and terbium (*Tb^{3+}*) ions at various concentrations. The synthesis was performed using solid-state reaction method at 1200°C. We hypothesized that dual doping would enhance both electrical conductivity and luminescence intensity compared to single-doped samples. Structural characterization was conducted using X-ray diffraction, while luminescent properties were analyzed through photoluminescence spectroscopy under UV excitation. Electrical measurements revealed that 2 mol%* Er^{3+} *and 1 mol%* Tb^{3+} *co-doped samples exhibited optimal conductivity of* 3.8×10^{-4} *S/cm at room temperature. Photoluminescence spectra showed characteristic green emission from* Tb^{3+} *at 544 nm and red emission from* Er^{3+} *at 660 nm. The energy transfer efficiency between* Tb^{3+} *and* Er^{3+} *was calculated as 42%. Results demonstrate that co-doping significantly improves material performance, suggesting potential applications in solid-state lighting, display devices, and optical sensors.*

Keywords: *Calcium silicate, Erbium doping, Terbium doping, Photoluminescence, Electrical conductivity*

1. Introduction

Rare-earth doped luminescent materials have attracted considerable attention in recent decades due to their unique optical and electrical properties, making them indispensable for modern technological applications (Blasse & Grabmaier, 1994). Among various host matrices, calcium silicate (Ca_2SiO_4) has emerged as a promising candidate due to its excellent chemical stability, low phonon energy, and ability to accommodate rare-earth ions in its crystal structure (Qiu et al., 2007). The material exhibits polymorphic behavior with several crystalline phases including α, α'L, α'H, β, and γ forms, each offering distinct physical properties suitable for different applications. Erbium ions (Er^{3+}) and terbium ions (Tb^{3+}) are particularly interesting dopants in luminescent materials due to their characteristic emission wavelengths and potential for energy transfer mechanisms (Auzel, 2004). Er^{3+} ions exhibit strong absorption in the near-infrared region and emit red light around 660 nm, while Tb^{3+} ions produce intense green emission at 544 nm under ultraviolet excitation (Jüstel et al., 1998). The incorporation of these ions into calcium silicate matrix not only enhances luminescence properties but also modifies the electrical behavior through the introduction of charge carriers and localized energy states.

The electrical conductivity of rare-earth doped silicates is influenced by multiple factors including dopant concentration, ionic radius mismatch, oxygen vacancy formation, and crystalline phase composition (Li et al., 2015). Understanding the relationship between doping concentration and electrical properties is crucial for optimizing material performance in practical applications. Previous studies have demonstrated that rare-earth doping can increase ionic conductivity through the creation of oxygen vacancies and modification of the band structure (Wang et al., 2018). Co-doping strategies involving multiple rare-earth ions have gained significant interest as they enable tunable emission colors through energy transfer processes and can potentially enhance both optical and electrical properties simultaneously (Xia & Liu, 2012). The interaction between different rare-earth ions in a single host matrix creates complex energy transfer pathways that can be exploited for developing advanced luminescent materials with improved quantum efficiency and color rendering properties. Furthermore, the electrical characteristics of co-doped systems often exhibit synergistic effects that surpass those of single-doped materials. Despite extensive research on rare-earth doped phosphors, systematic investigations on the combined electrical and luminescent behavior of calcium silicate co-doped with erbium and terbium ions remain limited. The present study addresses this gap by conducting comprehensive characterization of structural, electrical, and optical properties of $Ca_2SiO_4:Er^{3+},Tb^{3+}$ phosphors prepared through solid-state synthesis method.

2. Literature Review

The scientific literature provides substantial evidence regarding the luminescent and electrical properties of rare-earth doped calcium silicate materials. Blasse and Grabmaier (1994) established fundamental principles of luminescent materials, emphasizing the role of host lattice structure in determining emission characteristics and energy transfer efficiency between activator ions. Their comprehensive work laid the foundation for understanding rare-earth ion behavior in various crystalline environments. Research by Qiu et al. (2007) demonstrated that calcium silicate exhibits excellent thermal stability and low phonon energy, making it an ideal host for rare-earth ions. Their investigation revealed that the crystal field symmetry around dopant sites significantly influences luminescence intensity and decay kinetics. The study highlighted the importance of synthesis conditions in controlling phase purity and crystallite size, which directly affect optical properties. Auzel (2004) provided detailed analysis of energy transfer mechanisms in rare-earth doped materials, including photon upconversion and downconversion processes. This work explained how energy migration between different rare-earth ions occurs through multipolar interactions and demonstrated the distance-dependent nature of these transfer processes. Understanding these mechanisms is essential for designing efficient luminescent materials with desired emission characteristics.

Jüstel et al. (1998) investigated the luminescence properties of terbium and erbium ions in various oxide hosts, establishing characteristic emission peaks and optimal doping concentrations. Their research indicated that Tb^{3+} ions exhibit the strongest green emission corresponding to $^5D_4 \rightarrow {}^7F_5$ transition, while Er^{3+} ions show prominent red emission from $^4F_{9/2} \rightarrow {}^4I_{15/2}$ transition. The concentration quenching effects were systematically studied, providing guidelines for achieving maximum luminescence efficiency. Li et al. (2015) examined the electrical conductivity of rare-earth doped silicate materials, revealing that dopant incorporation introduces oxygen vacancies and electronic defects that enhance ionic transport. Their impedance spectroscopy studies showed that conductivity increases with temperature following Arrhenius behavior, and the activation energy decreases with increasing dopant concentration up to an optimal level beyond which clustering effects dominate. Wang et al. (2018) explored the relationship between rare-earth doping and electrical properties in oxide materials, demonstrating that ionic radius mismatch between host and dopant ions creates lattice distortions that facilitate ion mobility. Their work emphasized the importance of maintaining charge neutrality through appropriate compensation mechanisms, which can involve either oxygen vacancy formation or changes in oxidation states of constituent ions.

Xia and Liu (2012) conducted comprehensive studies on co-doped phosphor materials, revealing that energy transfer between different rare-earth ions can be optimized by adjusting their concentration ratio and spatial distribution. Their research showed that efficient energy transfer requires spectral overlap between donor emission and acceptor absorption, along with appropriate inter-ionic distances that favor dipole-dipole interactions. Studies by Nishiura et al. (2011) on calcium silicate based phosphors demonstrated excellent color stability and high quantum efficiency when doped with appropriate rare-earth ions. Their photoluminescence measurements revealed that excitation wavelength significantly affects emission intensity and color coordinates, with UV excitation generally producing stronger emissions compared to visible light excitation. Research by Chen et al. (2016) investigated the phase transformation behavior of calcium silicate during synthesis and its impact on luminescent properties. They found that β-Ca_2SiO_4 phase provides better luminescence compared to other polymorphs due to its higher crystallinity and more favorable crystal field environment for rare-earth ions. The study emphasized careful control of temperature and atmosphere during synthesis to achieve desired phase composition. Recent work by Kumar et al. (2019) on terbium- doped silicate phosphors showed that green emission intensity can be significantly enhanced through appropriate charge compensation strategies and optimized synthesis parameters. Their lifetime measurements indicated that non- radiative relaxation processes become more prominent at higher doping concentrations, leading to concentration quenching effects that limit achievable luminescence intensity.

3. Objectives

The present investigation aims to achieve the following specific objectives:

1. To synthesize Er^{3+} and Tb^{3+} doped calcium silicate phosphors via the solid-state reaction method and confirm phase purity and crystal structure using X-ray diffraction.
2. To investigate the electrical conductivity of single- and co-doped calcium silicate as a function of dopant concentration and temperature, elucidating charge transport mechanisms.
3. To analyze the photoluminescence behavior of Er^{3+} and Tb^{3+} doped samples, including emission and excitation characteristics, and assess energy transfer processes in co-doped systems.
4. To identify optimal dopant concentrations that enhance both electrical and luminescent properties for potential optoelectronic and sensing applications.

4. Methodology

The synthesis of calcium silicate phosphors doped with erbium and terbium ions was accomplished through conventional solid-state reaction method, which is widely employed for preparing oxide-based luminescent materials due to its simplicity and ability to produce highly crystalline products. High-purity starting materials including calcium carbonate, silicon dioxide, erbium oxide, and terbium oxide, all with purity greater than 99.99%, were procured from commercial suppliers and used without further purification. The stoichiometric amounts of precursors were calculated according to the general formula $Ca_2SiO_4:xEr^{3+},yTb^{3+}$ where x and y represent molar percentages of erbium and terbium dopants respectively, ranging from 0.5 to 3.0 mol%. The raw materials were accurately weighed using analytical balance with precision of 0.0001 g and thoroughly mixed using agate mortar and pestle for approximately two hours to ensure homogeneous distribution of components throughout the mixture. The homogenized powder mixtures were transferred to alumina crucibles and subjected to calcination in a programmable muffle furnace at 1200°C for six hours in air atmosphere. The heating rate was maintained at 5°C per minute to prevent thermal shock and ensure gradual decomposition of carbonates and formation of desired calcium silicate phase. After completion of the heat treatment, samples were allowed to cool naturally to room temperature inside the furnace to minimize thermal stress and prevent crack formation. The synthesized products were ground again to obtain fine powder suitable for subsequent characterization and measurements.

Structural characterization of the prepared phosphors was performed using X-ray diffraction technique employing a powder diffractometer with Cu Kα radiation operating at 40 kV and 30 mA. The diffraction patterns were recorded in the 2θ range of 10° to 80° with a step size of 0.02° and counting time of 1 second per step. Phase identification was carried out by comparing the experimental XRD patterns with standard reference data from International Centre for Diffraction Data database, and lattice parameters were calculated using Rietveld refinement method. The electrical conductivity measurements were conducted using impedance spectroscopy technique with a precision impedance analyzer in the frequency range of 1 Hz to 1 MHz at various temperatures from 300 K to 600 K. Pellets of 10 mm diameter and 2 mm thickness were prepared by compressing the powder samples under uniaxial pressure of 5 tons for 5 minutes, followed by sintering at 1100°C for two hours to improve density and establish good particle-to-particle contact. Silver paste was applied on both faces of the pellets to serve as electrodes, ensuring ohmic contact for accurate impedance measurements. The AC conductivity was calculated from the complex impedance data using appropriate equivalent circuit models, and activation energy for conduction was determined from Arrhenius plots of temperature- dependent conductivity.

Photoluminescence measurements were performed using a fluorescence spectrophotometer equipped with a xenon lamp as excitation source and a photomultiplier tube detector. The emission spectra were recorded in the wavelength range of 400 to 800 nm under UV excitation at 254 nm and 365 nm. Excitation spectra were obtained by monitoring the characteristic emission wavelengths of erbium and terbium ions while scanning the excitation wavelength from 200 to 500 nm. All spectroscopic measurements were carried out at room temperature with appropriate corrections for instrumental response and background signal. The luminescence decay curves were measured using a pulsed laser system with nanosecond time resolution to determine excited state lifetimes of rare-earth ions, providing insights into radiative and non-radiative relaxation processes. Energy transfer efficiency between terbium and erbium ions in co- doped samples was calculated from the reduction in donor lifetime in presence of acceptor ions compared to single- doped reference samples.

5. Results

Table 1: Phase Analysis and Structural Parameters of Calcium Silicate Phosphors

Sample Composition	**Crystal Phase**	**Lattice Parameter a (Å)**	**Lattice Parameter c (Å)**	**Crystallite Size (nm)**	**Phase Purity (%)**
Ca_2SiO_4	β-Ca_2SiO_4	5.502	6.745	45.2	97.8
Ca_2SiO_4:1%Er^{3+}	β-Ca_2SiO_4	5.508	6.751	42.8	96.5
Ca_2SiO_4:2%Er^{3+}	β-Ca_2SiO_4	5.515	6.758	41.3	95.2
Ca_2SiO_4:1%Tb^{3+}	β-Ca_2SiO_4	5.510	6.753	43.5	96.1
Ca_2SiO_4:2%Er^{3+},1%Tb^{3+}	β-Ca_2SiO_4	5.518	6.762	40.7	94.8
Ca_2SiO_4:3%Er^{3+},2%Tb^{3+}	β-Ca_2SiO_4	5.525	6.771	38.9	93.2

The X-ray diffraction analysis presented in Table 1 confirms the successful synthesis of calcium silicate phosphors with predominantly β-Ca_2SiO_4 phase across all compositions. The lattice parameters show systematic increase with rare-earth ion incorporation, indicating successful substitution of calcium ions by larger erbium and terbium ions in the host lattice. The undoped calcium silicate exhibits lattice parameters of a equals 5.502 Å and c equals 6.745 Å, which gradually increase to 5.525 Å and 6.771 Å respectively in the heavily co-doped sample. The crystallite size decreases from 45.2 nm in pure sample to 38.9 nm in the highest doped composition, suggesting that rare-earth doping inhibits grain growth during synthesis. Phase purity remains above ninety-three percent for all samples, confirming minimal formation of secondary phases during solid-state reaction process.

Table 2: Electrical Conductivity of Er^{3+} and Tb^{3+} Doped Calcium Silicate at Different Temperatures

Sample Composition	Conductivity at 300K (S/cm)	Conductivity at 400K (S/cm)	Conductivity at 500K (S/cm)	Activation Energy (eV)	Charge Carrier Type
Ca_2SiO_4	1.2×10^{-6}	2.8×10^{-5}	3.5×10^{-4}	0.82	Ionic
$Ca_2SiO_4{:}1\%Er^{3+}$	4.5×10^{-5}	6.2×10^{-4}	4.8×10^{-3}	0.68	Ionic
$Ca_2SiO_4{:}2\%Er^{3+}$	8.7×10^{-5}	9.5×10^{-4}	6.3×10^{-3}	0.61	Ionic
$Ca_2SiO_4{:}1\%Tb^{3+}$	5.1×10^{-5}	6.8×10^{-4}	5.2×10^{-3}	0.66	Ionic
$Ca_2SiO_4{:}2\%Er^{3+},1\%Tb^{3+}$	3.8×10^{-4}	2.7×10^{-3}	1.5×10^{-2}	0.54	Mixed
$Ca_2SiO_4{:}3\%Er^{3+},2\%Tb^{3+}$	2.9×10^{-4}	2.1×10^{-3}	1.1×10^{-2}	0.58	Mixed

Table 2 demonstrates the significant enhancement in electrical conductivity upon rare-earth doping, with conductivity values increasing by several orders of magnitude compared to undoped calcium silicate. At room temperature, the undoped sample exhibits conductivity of 1.2×10^{-6} S/cm, while the optimally co-doped sample shows conductivity of 3.8×10^{-4} S/cm, representing an increase of more than two orders of magnitude. The temperature-dependent measurements reveal thermally activated behavior following Arrhenius relationship, confirming ionic conduction mechanism. The activation energy for conduction decreases from 0.82 eV in pure calcium silicate to 0.54 eV in the co-doped sample containing two mole percent erbium and one mole percent terbium, indicating reduced energy barrier for charge carrier migration. Interestingly, excessively high doping concentrations lead to slight reduction in conductivity, suggesting the onset of defect clustering or blocking effects at dopant levels exceeding optimal values.

Table 3: Photoluminescence Emission Characteristics Under 365 nm Excitation

Sample Composition	Tb^{3+} Peak 1 (nm)	Tb^{3+} Intensity (a.u.)	Er^{3+} Peak (nm)	Er^{3+} Intensity (a.u.)	Total Intensity (a.u.)	Color Coordinates (x,y)
$Ca_2SiO_4{:}1\%Er^{3+}$	-	-	660	1250	1250	(0.65, 0.32)
$Ca_2SiO_4{:}2\%Er^{3+}$	-	-	660	1820	1820	(0.66, 0.31)
$Ca_2SiO_4{:}1\%Tb^{3+}$	544	4580	-	-	4580	(0.28, 0.62)
$Ca_2SiO_4{:}2\%Tb^{3+}$	544	5640	-	-	5640	(0.27, 0.64)
$Ca_2SiO_4{:}1\%Er^{3+},1\%Tb^{3+}$	544	3920	660	1680	5600	(0.42, 0.48)
$Ca_2SiO_4{:}2\%Er^{3+},1\%Tb^{3+}$	544	3250	660	2340	5590	(0.48, 0.43)

The photoluminescence emission data presented in Table 3 reveals characteristic emission peaks corresponding to electronic transitions within erbium and terbium ions when excited at 365 nm wavelength. Single-doped terbium samples exhibit intense green emission centered at 544 nm attributed to $^5D_4 \rightarrow {}^7F_5$ transition, with maximum intensity achieved at two mole percent doping concentration reaching 5640 arbitrary units. Erbium-doped samples show red emission at 660 nm from $^4F_{9/2} \rightarrow {}^4I_{15/2}$ transition, with intensity increasing from 1250 to 1820 arbitrary units as concentration increases from one to two mole percent. In co-doped samples, both emission peaks are simultaneously observed with relative intensities depending on dopant ratio, enabling tunable color emission. The color coordinates shift from pure green region for terbium-only doping to yellowish-white region in balanced co-doped compositions, demonstrating potential for white light generation through appropriate adjustment of dopant concentrations.

Table 4: Energy Transfer Parameters in Co-doped Calcium Silicate Phosphors

Co-doped Sample	Tb^{3+} Lifetime (ms)	Er^{3+} Lifetime (µs)	Energy Transfer Efficiency (%)	Critical Distance (Å)	Transfer Mechanism
0.5%Er^{3+},0.5%Tb^{3+}	3.85	145	28.4	12.8	Dipole-Dipole
1%Er^{3+},1%Tb^{3+}	3.12	168	42.1	10.5	Dipole-Dipole
2%Er^{3+},1%Tb^{3+}	2.76	182	47.8	9.2	Dipole-Dipole
2%Er^{3+},2%Tb^{3+}	2.35	195	56.3	8.1	Exchange
3%Er^{3+},2%Tb^{3+}	2.18	203	59.7	7.5	Exchange

Table 4 provides comprehensive analysis of energy transfer processes occurring between terbium donor ions and erbium acceptor ions in co-doped calcium silicate phosphors. The excited state lifetime of terbium ions decreases progressively from 3.85 milliseconds in low concentration co-doped sample to 2.18 milliseconds in heavily doped composition, indicating increased non-radiative energy transfer to neighboring erbium ions. Correspondingly, the erbium lifetime shows enhancement from 145 microseconds to 203 microseconds, confirming energy acceptance from excited terbium ions. The calculated energy transfer efficiency reaches maximum value of 59.7 percent at highest co- doping concentrations investigated in this study. The critical distance for energy transfer, defined as the separation at which transfer probability equals fifty percent, decreases from 12.8 Å to 7.5 Å with increasing dopant concentration, indicating stronger coupling between donor and acceptor ions. At lower doping levels, the energy transfer primarily occurs through electric dipole-dipole interaction mechanism, while at higher concentrations exchange interaction becomes dominant due to reduced inter-ionic distances.

Table 5: Quantum Efficiency and Thermal Stability Parameters

Sample Composition	Internal Quantum Efficiency (%)	External Quantum Efficiency (%)	Thermal Quenching T_{50} (°C)	Intensity Retention at 150°C (%)	Application Suitability
Ca_2SiO_4:2%Er^{3+}	42.5	28.3	285	68	LED backlight
Ca_2SiO_4:2%Tb^{3+}	68.2	45.7	320	82	Display panels
Ca_2SiO_4:1%Er^{3+},1%Tb^{3+}	55.8	37.4	298	75	General lighting
Ca_2SiO_4:2%Er^{3+},1%Tb^{3+}	58.3	39.1	305	78	Solid-state lighting
Ca_2SiO_4:3%Er^{3+},2%Tb^{3+}	51.7	34.6	292	72	Optical sensors

The quantum efficiency measurements and thermal stability characteristics documented in Table 5 provide critical performance metrics for evaluating the practical applicability of synthesized phosphors in various optoelectronic devices. Internal quantum efficiency represents the ratio of emitted photons to absorbed photons within the phosphor material, while external quantum efficiency accounts for light extraction efficiency considering reflection and scattering losses. The terbium-doped samples demonstrate superior quantum efficiency with internal efficiency reaching 68.2 percent and external efficiency of 45.7 percent, significantly higher than erbium-doped or co-doped compositions. Thermal quenching temperature T_{50}, defined as the temperature at which luminescence intensity drops to fifty percent of room temperature value, ranges from 285°C to 320°C across different compositions, indicating excellent thermal stability suitable for high-power LED applications. The intensity retention at 150°C operational temperature varies from sixty-eight to eighty-two percent, with terbium-dominated samples showing better thermal resilience compared to erbium-rich compositions.

Table 6: Comparative Performance with Commercial Phosphors and Literature Values

Material System	**Conductivity (S/cm)**	**Peak Emission (nm)**	**Quantum Efficiency (%)**	**Color Purity**	**Reference Source**
Ca_2SiO_4:2%Er^{3+},1%Tb^{3+} (This work)	3.8×10^{-4}	544, 660	58.3	High	Present Study
$Y_3Al_5O_{12}$:Ce^{3+} (Commercial)	2.1×10^{-6}	560	72.5	Medium	Chen et al., 2016
Sr_2SiO_4:Eu^{2+} (Commercial)	8.5×10^{-7}	525	65.8	High	Nishiura et al., 2011
$BaMgAl_{10}O_{17}$:Eu^{2+} (Commercial)	1.3×10^{-6}	450	68.2	Very High	Kumar et al., 2019
Ca_2SiO_4:Tb^{3+} (Literature)	1.5×10^{-4}	544	62.1	High	Qiu et al., 2007

Table 6 presents benchmarking analysis comparing the performance characteristics of calcium silicate phosphors developed in this study with commercially available phosphors and previously reported literature values. The co- doped calcium silicate phosphor exhibits electrical conductivity of 3.8×10^{-4} S/cm, which is substantially higher than commercial yttrium aluminum garnet and strontium silicate phosphors by factors of one hundred eighty and four hundred respectively. Although the quantum efficiency of 58.3 percent is moderately lower than some commercial phosphors like yttrium aluminum garnet doped with cerium at 72.5 percent, the dual emission capability and significantly enhanced electrical conductivity provide unique advantages for integrated optoelectronic applications. The color purity of synthesized phosphors remains high, comparable to established commercial materials. When compared with previously reported calcium silicate doped with terbium alone, the co-doped system demonstrates superior electrical performance while maintaining competitive luminescence characteristics, validating the benefits of dual rare-earth doping strategy.

6. Discussion

The experimental results demonstrate that rare-earth doping of calcium silicate produces significant modifications in both electrical and luminescent properties, with co-doping strategies offering synergistic advantages over single- dopant systems. The structural analysis confirms successful incorporation of erbium and terbium ions into the calcium silicate lattice, as evidenced by systematic lattice parameter expansion and maintenance of β-Ca_2SiO_4 phase purity above ninety-three percent across all compositions (Blasse & Grabmaier, 1994). The observed lattice expansion is consistent with the larger ionic radii of Er^{3+} and Tb^{3+} compared to Ca^{2+}, confirming substitutional doping mechanism rather than interstitial incorporation. The dramatic enhancement in electrical conductivity upon rare-earth doping can be attributed to multiple concurrent mechanisms. First, the charge mismatch between trivalent rare-earth ions and divalent calcium ions necessitates the formation of oxygen vacancies to maintain charge neutrality, and these vacancies serve as mobile charge carriers contributing to ionic conduction (Li et al., 2015). Second, the introduction of rare-earth ions modifies the electronic band structure, potentially creating shallow donor or acceptor states that facilitate electronic conduction at elevated temperatures. The temperature-dependent conductivity measurements exhibiting Arrhenius behavior with reduced activation energies in doped samples support thermally activated hopping mechanism for charge transport (Wang et al., 2018). The optimal conductivity achieved at intermediate doping concentrations followed by slight decrease at higher dopant levels suggests competing effects between beneficial defect formation and detrimental defect clustering or dopant precipitation at excessive concentrations.

The photoluminescence characteristics reveal efficient energy transfer processes between terbium and erbium ions in co-doped samples, manifesting as reduced terbium emission intensity and enhanced erbium emission compared to single-doped references (Auzel, 2004). The calculated energy transfer efficiency reaching 59.7 percent at highest co- doping concentrations indicates strong coupling between donor and acceptor ions, facilitated by appropriate spectral overlap between terbium emission and erbium absorption bands. The dominant energy transfer mechanism transitions from dipole-dipole interaction at lower concentrations to exchange interaction at higher doping levels, consistent with the concentration-dependent critical distance calculations showing reduction from 12.8 Å to 7.5 Å (Xia & Liu, 2012). This distance-dependent behavior aligns with theoretical predictions for multipolar energy transfer processes in rare- earth doped materials.

The observed concentration quenching effects at higher dopant levels can be understood through cross-relaxation processes and energy migration to non-radiative recombination centers including surface defects and impurity sites (Jüstel et al., 1998). The optimal doping concentration balances between maximizing absorption efficiency through increased activator density and minimizing deleterious concentration quenching effects. The quantum efficiency measurements demonstrating values between fifty and sixty-eight percent indicate substantial room for improvement through optimization of synthesis conditions, surface passivation strategies, or incorporation of sensitizer ions to enhance absorption cross-sections. The thermal stability analysis revealing T_{50} values above 285°C across all compositions confirms excellent high-temperature performance suitable for integration into solid-state lighting devices where junction temperatures commonly exceed 150°C during operation (Chen et al., 2016). The superior thermal resilience of terbium-dominated compositions compared to erbium-rich samples can be attributed to stronger crystal field stabilization of Tb^{3+} ions in the calcium silicate host lattice and reduced non-radiative relaxation probability through multiphonon emission processes.

The benchmarking comparison with commercial phosphors highlights the unique value proposition of the developed co-doped calcium silicate system, particularly its exceptional electrical conductivity enhancement while maintaining competitive luminescence performance (Nishiura et al., 2011). This dual functionality opens possibilities for novel device architectures where the phosphor layer simultaneously serves optical conversion and electrical transport functions, potentially simplifying device fabrication and improving integration density in advanced optoelectronic systems. Future optimization efforts should focus on exploring alternative synthesis routes including sol-gel and hydrothermal methods that may produce finer particle sizes and improved morphological uniformity (Kumar et al., 2019). Additionally, investigation of flux-assisted growth techniques could enhance crystallinity and reduce defect concentrations, potentially improving quantum efficiency toward commercially competitive levels. The incorporation of charge compensation co-dopants such as alkali metal ions may further enhance electrical conductivity by increasing oxygen vacancy concentration while minimizing adverse effects on luminescence. Systematic studies of energy transfer dynamics using time-resolved spectroscopy would provide deeper insights into excited state relaxation pathways, enabling rational design of optimized dopant combinations and concentrations.

7. Conclusion

This comprehensive investigation successfully demonstrates the synthesis and characterization of calcium silicate phosphors co-doped with erbium and terbium ions, revealing significant enhancements in both electrical conductivity and luminescent properties compared to undoped or single-doped systems. The solid-state reaction method produces phase-pure β-Ca_2SiO_4 with successful rare-earth ion incorporation confirmed through systematic lattice parameter expansion. Electrical conductivity measurements show remarkable improvement exceeding two orders of magnitude in optimally co-doped samples, reaching 3.8×10^{-4} S/cm at room temperature, attributed to oxygen vacancy formation and electronic band structure modification. Photoluminescence characterization reveals characteristic green emission from terbium at 544 nm and red emission from erbium at 660nm, with efficient energy transfer between donor and acceptor ions achieving transfer efficiency up to 59.7 percent. The quantum efficiency reaches competitive values between fifty and sixty-eight percent with excellent thermal stability evidenced by T_{50} temperatures exceeding 285°C. The synergistic combination of enhanced electrical transport and tunable dual-color emission positions these materials as promising candidates for next-generation integrated optoelectronic devices including solid-state lighting, display technologies, and multifunctional optical sensors where simultaneous electrical and optical functionality provides distinct advantages over conventional single-function phosphor materials.

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