

Synthesis and Photoluminescence Properties of Europium-Doped Calcium Aluminate Phosphors for Solid-State Lighting Applications

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ARTICLE DETAILS	ABSTRACT
Research Paper Received: 26-08-2026 Accepted: 25-09-2026 Published: 20-10-2026 Keywords: Optical emission, Calcium aluminate, Oxidation state of europium	The optical emission tunability, chemical stability, and applications in solid-state lighting, display technologies, optical sensing, and persistent luminescence systems of europium doped calcium aluminate phosphors have made them a subject of massive research interest. They are influenced by various factors that are connected with one another, such as the composition and crystal structure of the calcium aluminate host, oxidation state of europium, dopant concentration, synthesis conditions, defect chemistry, and post-synthesis heat treatment. The main synthesis routes used to produce calcium aluminate phosphors doped with europium are reviewed and discussed critically with special emphasis on the conventional solid-state route, combustion synthesis, sol-gel processing and other wet-chemical synthesis methods. The mechanism of the Eu^{2+} and Eu^{3+} photoluminescence is explained using their electronic configuration, their local crystallographic and the mechanism of their excitation and emission. The review also includes a discussion on the energy storage mechanisms of phase formation, particle morphology, concentration quenching, thermal stability, charge

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compensation and defect-mediated energy storage. The difference between prompt photoluminescence and long-persistent luminescence are emphasized, as these two phenomena may be related but distinct. Studies reported indicate that Eu^{2+} -activated calcium aluminates have broad blue emission, while Eu^{3+} -activated compositions generally have characteristic red or orange-red emission. These behaviours are not universal though and vary according to host phase and synthesis environment. There are several papers available that suggest that it is necessary to control the europium valence, to minimise secondary phases and to understand the trapping and recombination processes to achieve reproducible optical performance. Last, challenges on phase purity, reproducibility, thermal quenching, quantitative comparison and device level validation are addressed. The review serves as a reference tool for the evaluation of current studies and the development of future studies, without using results from literature as the ones to be measured. In order to understand the role of Eu^{3+} , Eu^{2+} , and the combustion synthesis in the production of the calcium aluminate, the photoluminescence of this material was examined. The photoluminescence of calcium aluminate was studied to understand the role of Eu^{3+} , Eu^{2+} and combustion synthesis in the production of the calcium aluminate.

1. Introduction

1.1 Background and significance

As the efficiency of solid-state lighting (SSL) has grown, so too has the demand for luminescent materials to make the light emitted by semiconductor light sources useful and bright in the visible spectrum. Light emitting diodes (LED) can provide benefits of energy efficiency, size, long life, and design flexibility. However, the spectrum emitted by an LED chip will not always yield the desired spectrum for general illumination. Phosphors are then used to absorb some of the incident radiation and remain to emit long wavelength energy and thus, combinations of blue, green, yellow, orange and red emission are used to produce white light or other colors. The performance of the phosphor can also be influenced both by the type of luminescent activator and also by the type of host lattice in which it is contained. The host affects

local coordination environment, electronic energy levels, lattice vibrations, defect population and the probability of non-radiative relaxation. Of particular interest are oxide-based hosts, which may provide chemical stability and be used in conjunction with high-temperature processing. Alkaline-earth aluminates are one of the significant families of luminescent materials among these. Calcium aluminate compositions have been studied as hosts of rare-earth activators due to their ability to accommodate various structural arrangements and their ability to be prepared by various ceramic and solution preparation techniques. Calcium aluminate is not a single phase, but a group of compounds with the composition CaAl_2O_4 , CaAl_4O_7 , and $\text{CaAl}_{12}\text{O}_{19}$, which have different local cation environments, crystal structure and stoichiometry. These differences have consequences on the incorporation and optical properties of Eu^{3+} ions.

Thus any consideration of europium-doped calcium aluminates requires separation between the compositions of the host and not their whole class of calcium- aluminium oxides as a spectroscopically equivalent class. Europium is particularly useful as a luminescent activator, because two optically important oxidation states of europium, Eu^{2+} and Eu^{3+} , exist. The two states are different in their electronic configuration and have in general different emission characteristics. The Eu^{2+} emission is primarily due to transitions between the excited $4f^65d^1$ configuration and the ground $4f^7$ configuration. Eu^{2+} emission usually occurs as a broad band, whose position is related with the surrounding crystal field structure, due to the strong interaction between the $5d$ state and the surrounding crystal field. Eu^{3+} , on the other hand, has characteristic intra $4f$ transitions, often with relatively narrow emission lines in the orange-red region. Consequently the optical properties of the europium-doped calcium aluminates cannot be described by the concentration of the dopant. The oxidation state of europium, local symmetry, phase composition, synthesis atmosphere and defect chemistry all must be taken into consideration. For instance, Singh et al. (2007) studied the combustion-synthesized CaAl_2O_4 doped with europium and found evidence of divalent europium. Eu^{2+} doped in calcium aluminates has been studied for blue emission and afterglow, and Eu^{3+} doped $\text{Ca}_2\text{Al}_2\text{O}_5$ for red emission has been studied. The results show a wide range of optical properties of the calcium aluminate systems. They also demonstrate the need to consider synthesis and characterization simultaneously – the same compositions can have different optical response due to variations in processing conditions, such as changes in phase formation or valence state of europium. The luminescent hosts, calcium aluminates are described in the first section,

1.2. To be suitable for phosphor application, a crystalline host should possess a number of structural and chemical properties. These are: cation sites available for accommodating the activator, local coordination of

the cation sites, lattice rigidity, defect formation energies, and the relationship of the excited states of the activator and the electronic structure of the host. There are many sites in which calcium ions can be replaced by divalent europium ions in an isovalent fashion. In such cases, replacement of Ca^{2+} with Eu^{2+} does not need to be charge-compensated. When europium is present as Eu^{3+} , however, it introduces an effective charge imbalance when substituted at a divalent calcium site. Depending on the composition and processing environment compensation can be by vacancies, other defects, or coupled substitutions. Such possibilities affect the structural stability and the optical behavior of the material. Calcium aluminates are structurally complex compounds, and details of their structure are essential in interpreting published spectra. Europium-doped calcium aluminate can be a type of CaAl_2O_4 , another calcium aluminate phase, or a combination of phases. The different phases confer different local environments for europium and may also give rise to new luminescent centres and/or non-radiative pathways. Therefore, X-ray diffraction (XRD) is required for phase identification, but the fact that secondary-phase peaks are not visible does not guarantee absolute phase purity. The host may also affect the energy needed to excite europium and the efficiency in which absorbed energy is emitted. The shift of emission bands or their width can be caused by the differences in CF strength, covalency, lattice relaxation, and phonon coupling. These effects are vital to understanding why europium emission cannot be reliably predicted from the chemical formula alone.

1.3 Research problem

Europium doped calcium aluminate phosphors have been investigated by several synthesis methods, but a comparison between the various methods is not easy to carry out in the literature. Precursor purity, dopant concentration, fuel-to-oxidizer ratio, calcination temperature, atmosphere, heating rate, cooling procedure, and characterization method may vary among the studies. Furthermore, certain investigations are directed towards the prompt photoluminescence, while others are oriented towards the afterglow behaviour. These properties are correlated with the electronic and defect structure of the material but are not synonymous measurements of performance. Materials with strong emission under sustained excitation may not have a long afterglow following the removal of the exciter. Likewise, with good emission at room temperature, there is no guarantee that the device has high quantum efficiency, good thermal stability, or practical application for a commercial LED product. Evaluation means something only if the measured property and the experimental conditions used to obtain it can be clearly defined. Another problem is the oxidation state of europium. In some compositions, Eu^{2+} and Eu^{3+} can coexist and their relative proportions in the composition may vary as a function of the processing conditions. Emission band assignments, without supporting structural or spectroscopic data, can then result in incomplete interpretations. These limitations

will be important for devising reproducible synthesis strategies and for making defensible comparisons with published work.

1.4 Aim and objectives

This review aims to critically review synthesis, structure, mechanisms of photoluminescence and solid-state lighting applications of europium doped calcium aluminate phosphors. The objectives are: To describe the structural and chemical properties of the host phases relevant to europium incorporation, calcium aluminate.

2. To match up the principal synthesis techniques and their strengths and weaknesses.

3. To compare the optical properties of Eu^{2+} - and Eu^{3+} -activated calcium aluminates. To assess the importance of dopant concentration, defects, local coordination and thermal processing to luminescence. To differentiate prompt photoluminescence from persistent luminescence and talk about the various characterisation needs. To outline the gaps in the current knowledge and make suggestions for future experimental studies. The scope of the review is 1.5. This paper is a critical review of literature and not a report of a new laboratory experiment. It integrates published research and established photophysical principles related to the europium activated calcium aluminates and relates to other aluminate studies performed by the alkaline-earth aluminates where they elucidate general mechanisms. It is not a synthetic generator, it is not a retrieval or measurement tool for spectra, it does not measure quantum yields, nor does it conduct statistical analyses. This is important because the measurements reported are from the original studies. Only quantitative values are included when they can be referred to a published source and related to the context of the experiments. If there is no appropriate comparable dataset, then there isn't a new numerical dataset, effect size, confidence interval or statistical significance test derived from the literature.

2. Review Methodology

2.1 Review design

The paper uses critical narrative review method. It is suitable for a research area where studies address the various calcium aluminate phases, methods of synthesis, europium oxidation state and optical endpoints. Using a narrative synthesis, structural chemistry, processing conditions and luminescence mechanisms can be factored in simultaneously, with differences between individual studies acknowledged. The review is divided into four related themes: synthesis and phase formation, europium incorporation and valence, photoluminescence mechanisms, and implications for solid-state lighting. Where the mechanisms of persistent luminescence or its indicators deviate from those of prompt emission, research on persistent

luminescence is treated separately. The principles of literature identification and literature selection are discussed in 2.2. The scholarly databases and platforms of the publishers provide a way to identify relevant literature, with Web of Science, Scopus, Google Scholar, Crossref and PubMed being used where possible and the material-science journals' website. They are searched under various combinations of “solution combustion synthesis,” “ CaAl_2O_4 ,” “Europium-doped calcium aluminate,” “europium-doped calcium aluminate phosphor,” “ $\text{CaAl}_2\text{O}_4\text{:Eu}^{3+}$ emission,” “ $\text{CaAl}_2\text{O}_4\text{:Eu}^{2+}$ photoluminescence,” “sol–gel synthesis,” and “persistent luminescence.” Studies are most relevant if they report the composition of the host, how it was prepared, its characterization, and optical measurements. Research work on related strontium and barium aluminates is valuable for understanding the general behaviour of the activators but cannot be used as direct experimental evidence for the behaviour in all calcium aluminate compositions. Original research articles, well-documented review papers and articles with adequate bibliographic data to enable re-checking are preferred. The results of the various phases or measurement conditions should not be pooled as if they were one and the same experiment. This is a narrative review and not a registered systematic review. It does not make any claim that it is a complete database search, nor exhaustive screening, nor a formal risk-of-bias assessment. A journal publication reporting a systematic review should include documented dates of search, exhaustive database-specific search strings, screening criteria, duplicate removal procedures and an easily reproducible study-selection record.

2.3 Approach to evidence synthesis

Literature is compared on the basis of the material composition, synthesis route, Eu oxidation state, structural characterization, excitation and emission behaviour, and application. Mechanistic explanations are considered in the context of known photophysics and the results presented by the study concerned. Brightness is subject to special precautions. Absolute quantum yield, integrated emission intensity, peak intensity, decay lifetime, afterglow duration and perceived brightness are all different quantities. They should not be substituted for each other. Similarly, only comparisons of emission intensities that are sufficient for the excitation power, sample geometry, instrument settings, and data normalization are meaningful. There are therefore trends and mechanisms highlighted, not a pooled numerical estimate from incompatible experiments, as the review focuses on the trend of the evidence, not on its aggregate.

3. Crystal Chemistry of Calcium Aluminate Hosts

3.1 Major calcium aluminate phases

Calcium aluminate materials are not a single crystal structure but are a family of compositions. CaAl_2O_4 , CaAl_4O_7 , and $\text{CaAl}_{12}\text{O}_{19}$ are different forms of calcium and aluminium. The formation is determined by the composition of the precursors, the reaction temperature, diffusion and thermal history. CaAl_2O_4 is a material that has been thoroughly explored as a host for blue-emitting and persistent phosphors containing europium. Peng and co-workers, and subsequent combustion synthesis studies, have reported blue emission in this host with Eu^{2+} , even in the $\text{CaAl}_2\text{O}_4^{2+}, \text{Nd}^{3+}$ system studied. On the other hand, Eu^{3+} -activated calcium aluminates can emit characteristic red or orange-red color from the europium 4f shell. A certain calcium aluminate phase formation is sensitive to the Ca ratio. Secondary phases caused by an inappropriate precursor ratio or incomplete reaction may change the emission properties. The authors of dejene et al. (2010) discussed the changes in structure and emission of $\text{CaAl}_x\text{O}_y^{2+}$ phosphors, which were prepared by solution combustion. The actual phase composition needs to be determined, not assumed, based on the nominal recipe, as this study has shown.

3.2 Crystal-field effects

Lattice surrounding influences the electronic states of luminescent activator. The excited 5d electron in Eu^{2+} has a strong host interaction. The crystal field splitting and the interactions between the neighbouring ions and the activator affect the energies of the 5d states. As a result, the energy gap between the relaxed excited state and the ground state is different in the hosts and crystallographic sites. The emission wavelength may change, the emission band may become broader and/or reshaped, and the probability of non-radiative relaxation may be changed by a change in local environment. If there are more than one appropriate calcium site within a host, europium can enter the site with two different coordination numbers. This can result in several emission components or in wider spectral profiles. The assumption that all Eu^{2+} ions of the same nominal composition are in a uniform environment is not sufficiently adequate to describe the relationship between the crystal-field effects and the emission. A distribution of activator environments might result from local structural disorder, defects and phase mixtures. The incorporation of Eu and charge compensation were explored. The incorporation of Eu and charge compensation were investigated. The energetics of defect formation, site preference, oxidation state and ionic size all play a role in the incorporation of europium. The size difference may give rise to local lattice distortion, but Eu^{2+} can replace Ca^{2+} without the formal charge mismatch. However, substitution of the Eu^{3+} ion for a Ca^{2+} ion site necessitates charge compensation unless it occurs by a coupled process. Ca Vacancies, Oxygen defects, coupled substitution with other cations are possible compensating defects. The defect population is a function of chemical composition, chemical potential of oxygen, synthesis atmosphere, and thermal

treatment. Not all the calcium aluminate compositions are expected to have a single defect mechanism. Defects are significant for charge compensation, charge-carrier transport, and changing the luminescence efficiency. Defects may help in the case of energy storage through them for persistent luminescence, but hinder in the case of efficient non-radiative pathways. Inadequate structural disorder and phase purity. Lattice defects, remaining precursor related species, grain boundaries and minor crystalline phases can occur within a nominally europium doped calcium aluminate. Both of them are able to affect transfer of excitation and emission. Too much disorder can result in the creation of additional sites with different local environments to which Eu^{2+} can be confined, thereby broadening the emission, but the increased disorder can also lead to additional non-radiative losses. XRD is a technique used for determining the presence or absence of crystalline phases and to determine if the peaks associated with them are the desired host. But peak broadening may occur due to various reasons such as crystallite size and microstrain, and cannot be considered as a proof of the existence of nanoscale particle size. Likewise, scanning electron microscopy (SEM) imaging can be used to detect the morphology of the particles, but not the crystallographic phase or the valence of europium. Hence, a strong characterization strategy is a combination of complementary strategies. An XRD can determine the predominant crystalline phase, an electron microscopy can study the morphology, elemental analysis gives information about the composition and optical or absorption based spectroscopy can give information about the activator. If the assignment of oxidation states is crucial to the understanding, it is important to consider using X-ray absorption spectroscopy or some appropriate valence-sensitive technique in addition to the emission spectra. Practice of synthesis of Europium-Doped Calcium Aluminate Phosphors.

4.1 Conventional solid-state reaction

The conventional solid-state reaction method is a well-developed route to make the crystalline oxide phosphors. In this process, suitable amounts of calcium-containing and aluminium-containing raw materials are combined with a source of europium and thermally treated. The resulting material is ground, calcined and, if required, annealed in an atmosphere controlled environment. The major benefit of this technique is the simple chemistry and ability to prepare relatively large quantities of ceramic powders. It may also facilitate the good crystallinity under the proper precursor mixing and reaction conditions. But the synthesis of solid-state is usually carried out at relatively high temperatures and for longer durations to achieve diffusion and phase formation. The degree of mixing can result in compositional inhomogeneity if it is not sufficient or particle coarsening and unwanted phases if it is too high. The latter is not solely a function of temperature in the case of the calcium aluminates doped with europium. Other factors such as the calcium to aluminium ratio, dopant concentration, atmosphere, cooling parameters, and the use of fluxes also impact



the outcome. The atmosphere is particularly important in the synthesis: the oxidation state of europium can change on heating and cooling the material, so it is important to include the atmosphere in the synthesis design, not just as an incidental detail.

4.2 Solution combustion synthesis

Various methods have been explored to produce the rare-earth (RE) doped calcium aluminate, including solution combustion synthesis. The process normally uses soluble metal salts, which are blended in a particular fuel. After dehydration and ignition, solid powder is formed by an exothermic reaction. Various formulations using urea and related organic compounds as fuel have been used. There are a number of potential benefits to combustion synthesis. Rapid heat releasing can help to ensure the formation of oxides, and the evolution of gas may lead to the production of porous powders with a relatively low apparent density. The approach can also minimize the amount of external heating time compared to other ceramic methods. Singh et al. (2007) already showed the preparation of Eu-activated CaAl_2O_4 using nitrate–urea combustion method and other studies have been conducted on the combustion derived calcium aluminate phosphors with Eu^{2+} and other rare-earth ions. However, the fast synthesis cannot ensure phase purity, uniform dopant distribution and high luminescence efficiency. There can be spatial variations in combustion temperature and secondary phases may be present in the final powder if the precursor stoichiometry or the reaction conditions are not optimal. The amount and type of fuel will affect combustion behavior, gas evolution, porosity and local thermal history. Another drawback is that the oxidation state achieved at the end of combustion might not be ideal for the use. Europium added as a trivalent precursor is not completely trivalent, nor is it always fully converted to the divalent state. Further annealing may be necessary. In a 2024 review, Panda et al. explain combustion synthesis as a significant method for the synthesis of calcium aluminate-based phosphors and the significance of rare-earth activation and persistent luminescence. This literature provides evidence of the benefits of combustion synthesis as well as evidence for systematic optimization.

4.3 Sol–gel synthesis

In an alternate route, the sol–gel processing method can be used to obtain compositional homogeneity by molecular or nanoscale mixing of precursors. The sol can be made by using metal alkoxides, nitrates, chelating agents, and suitable solvents, and then the sol transforms into a gel. Volatile or organic components are removed by drying and/or thermal treatment to obtain the desired oxide phase. The most likely benefit is enhanced mixing at the precursor concentration, which may be beneficial in cases where the precursor concentration is low. Some sources of compositional variation can be decreased by a more

homogeneous precursor. The final step still relies on the process of precursor decomposition, crystallization and heat-treatment conditions chosen. However, challenges such as use of solvent, precursors' cost, drying shrinkage, organic residues, and long processing time are also introduced by the sol–gel process. Furthermore, the formation of a homogeneous gel does not indicate a single-phase ceramic. XRD and suitable compositional analyses are still needed. The post-synthesis atmosphere is an important factor in the preparation of $\text{CaAl}_2\text{O}_4^{2+}, \text{Nd}^{3+}$ by a non-aqueous sol–gel process. Annealing in air has been reported to maintain europium mostly in the trivalent state while subsequent annealing in a reducing atmosphere of nitrogen–hydrogen can favour the formation of Eu^{2+} . These results highlight the difference between precursor homogeneity and the control of the final valence of the activator. Other wet-chemical and solution based approaches

4.4. Other strategies are: coprecipitation, polymer-assisted precursor processing, hydrothermal treatment, and related solution-based strategies. They are suitable for the different phases, powder morphology, available equipment and thermal stability of the precursor system. Precipitation conditions can be carefully controlled to achieve a fairly even distribution of cations by coprecipitation. However, the precipitation behavior of calcium and aluminium species can vary, possibly leading to compositional variations. Additionally, washing/drying may also influence the agglomeration and precursor chemistry. In the hydrothermal processing, crystallization control is possible in a pressurized aqueous environment. But, further heat treatment might be needed to make the desired calcium aluminate phase for the composition and process. It is important, therefore, to consider the entire preparation route, not only the first reaction, when evaluating hydrothermal synthesis. The use of polymer-assisted methods for precursor mixing and effect on particle formation can enhance. However, when a reduction of europium is significant, other factors must be taken into account such as the presence of residual carbon, incomplete decomposition, and variations in the local atmosphere. There is not any single best technique. For comparison, the composition of the target and the characteristics for comparison must be the same. Post-synthesis annealing and atmosphere control

4.5 Post-synthesis treatment can help to decide the final material phase/oxydation state of europium. Oxidizing, inert and reducing atmosphere create different oxygen chemical potential that can influence the formation or stability of defects. Eu^{2+} is often preferred for the case of wide band blue emission in the calcium aluminate hosts. But it may be necessary to reduce the starting material to Eu(II) before it can be obtained. Reaction efficacy is dependent on temperature, time, gas composition, sample geometry and chemical nature of the host. The higher the annealing temperature, the better the crystallinity and the greater the europium reduction but can also lead to an increase of the particle size, defect populations and powder

colour. Thus, the maximization of the intensity of one emission band is not necessarily the same as the optimization of the overall phosphor. Samples to be compared should be treated under controlled conditions and a systematic study should be carried out to establish whether phase evolution, changes in europium valence or changes in defect chemistry are linked to a change in emission.

Table 1

Comparison of Major Synthesis Routes for Europium-Doped Calcium Aluminate Phosphors

Synthesis route	Principal advantages	Important limitations	Essential characterization
Solid-state reaction	Established process; suitable for ceramic-scale production	Diffusion limitations; high-temperature processing; possible particle coarsening	XRD, SEM, elemental analysis, photoluminescence
Solution combustion	Rapid reaction; potentially porous and finely divided powders	Sensitive to fuel ratio and combustion conditions; possible secondary phases	XRD, SEM, excitation and emission spectra
Sol-gel processing	Good precursor mixing; potential compositional uniformity	Solvent and precursor requirements; drying and decomposition challenges	XRD, thermal analysis, SEM, valence-sensitive analysis
Coprecipitation	Potentially homogeneous cation distribution; solution-based processing	Different precipitation behaviours; washing and agglomeration	XRD, compositional analysis, SEM
Hydrothermal processing	Controlled solution-mediated crystallization	Pressure equipment; phase formation may require further heating	XRD, microscopy, photoluminescence
Post-synthesis annealing	Can improve crystallinity and modify europium valence	Grain growth; atmosphere-dependent defect changes	XRD, photoluminescence, suitable valence-sensitive spectroscopy

Note. This table provides a qualitative synthesis of established processing principles. It is not the result of a controlled comparative experiment, and the relative advantages depend on the composition and processing conditions.

5. Photoluminescence Mechanisms

5.1 Fundamentals of photoluminescence

Photoluminescence is the emission of photons by a material which was excited by incident radiation, as the excited electronic states decay. This process consists of excitation, energy transfer and/or relaxation, and radiative emission. Some of the absorbed energy can be reradiated in another form, such as lattice vibrations, or released as other types of energy instead of as light. The observed emission spectrum is a function of the electronic structure of the activator, the host structure, and the relaxation channels. An excitation spectrum gives information on the wavelengths that can be used to get emission at a certain detection wavelength, and an emission spectrum gives information on the wavelengths emitted under a certain excitation condition. The amount of material, the intensity of the excitation source, the absorption, the collection geometry of the spectrograph and the sensitivity of the instrument and the sample scattering influence the Photoluminescence intensity. It is therefore not a direct measure of the quantum efficiency unless the measurement procedure is designed to establish the quantum efficiency.

5.2 Eu^{2+} emission

EuII is divalent; its ground-state is $4f^7$. Excited configurations can be represented as $4f^65d^1$ and can be formed by optical excitation. Emission is the transition to the ground state $4f^7$ configuration. The $5d$ orbitals are more space extensive compared to the $4f$ orbitals and they have more lattice interaction. This splitting of crystal-field and host-dependent energy levels will affect the emission wavelength. The emission is often wide in Eu^{2+} -activated phosphors due to a high lattice vibration coupling as well as the fact that various activator sites can contribute to the emission spectrum. The emission of blue light is especially important for CaAl_2O_4 phosphors. Peng et al. (2007) reported the blue emission with peak value around 440 nm in $\text{CaAl}_2\text{O}_4^{2+}, \text{Nd}^{3+}$ material fabricated by combustion processing. This wavelength is a result of that published work of that particular study and does not mean it will be applicable to all calcium aluminate compositions and all synthesis paths. The lattice relaxation, site occupation, host phase and temperature determine the emission position and width of Eu^{2+} . Thus, variations in peak wavelength between two studies may not only be experimental error, but real structural differences as well.

5.3 Eu^{3+} emission The electronic structure of trivalent europium is $4f^6$. The characteristic visible emission is due to transitions between the excited and lower lying $4f$ states. These states are relatively protected, and Eu^{3+} emission may manifest as a series of relatively narrow lines. The Eu^{3+} spectra are usually interpreted by means of prominent transitions between an excited ($^5\text{D}_0$) state and lower ($^7\text{F}_J$) ones. The transition ($^5\text{D}_0 \rightarrow ^7\text{F}_1$) is often referred to as a magnetic dipole transition, while the transition ($^5\text{D}_0 \rightarrow ^7\text{F}_2$) is often called a local environment sensitive and electric dipole selection-rule relaxation. The ratio of the intensities of these transitions can give clues to the symmetry and chemical surroundings of europium. The use of multiple sites and overlapping bands, as well as differences in the sample composition, can affect the measured spectrum, however, conclusions about site symmetry must be drawn with caution. The excitation around 396 nm and the red emission features near 594 and 616 nm have been reported for the research of $\text{Ca}_2\text{Al}_2\text{O}_5^{3+}$, and have been assigned to the characteristic transition of Eu^{3+} . The values are reported composition and method of preparation, not universal values for the calcium aluminate host. Therefore, the CaAl_2O_4 -based calcium aluminates could be applicable if an orange-red emission is needed. They are used for lighting applications because of their efficiency to emit light, thermal stability, compatibility of excitation absorption, and the contribution of their spectrum in the target device.

5.4 Mixed $\text{Eu}^{2+}/\text{Eu}^{3+}$ behaviour

Some host compositions and processing conditions allow the simultaneous presence of Eu^{2+} and Eu^{3+} . This co-existence may yield a wide-band emission from Eu^{2+} as well as more pronounced lines of Eu^{3+} emission. This depends on the relative numbers of the different oxidation states, the local environment, and the pathways for their excitation and relaxation. Just because the emission spectrum is complicated, it is not necessarily a mixed valence behaviour. Completeness of the spectrum can also be due to several phases, defects, or crystallographic sites. Complementary evidence is needed for stronger assignments, for which optical and valence-sensitive characterization methods are necessary. The ratio of Eu^{2+} to Eu^{3+} can vary during the annealing process. Any changes in this composition can alter the spectral distribution even if the nominal europium concentration remains the same. Therefore, atmosphere or heat treatment should be sufficiently described so the results can be replicated.

Figure 1

Conceptual Energy-level Diagram for europium-activated calcium aluminate phosphors. The structure of the manuscript as suggested:

Panel A — Eu^{2+} : Demonstrate $4f^7$ ground state configuration, excitation to $4f65d1$ excited state, return to the ground state, and broad band radiative emission. For Eu^{3+} , the transitions shown in

Panel B are those for the excitation to higher $4f^6$ states followed by relaxation to the ($^5D_0$) emitting state, and line-like transitions to the (^7F_J) states. Show excitation, trapping of charge carriers, thermal release from traps, and subsequent recombination associated with delayed emission in

Panel C — Defect mediated persistence. Note. This is a proposed schematic to explain the luminescence of the material, based on known luminescence mechanisms. It is not an experimentally measured energy-level diagram for a particular calcium aluminate sample. Energy positions and transition intensities should only be added if there is adequate material-specific evidence supporting them. Explain the principles of excitation and emission spectra. Excitation spectra are generated by scanning the emission at a fixed wavelength while varying the excitation. They can indicate the optical absorption channels that lead to the observed emission. The process of recording emission spectra is done by setting the excitation wavelength and measuring the intensity of emitted light over a range of wavelengths. In the case of Eu^{2+} the excitation bands can be transitions from the ground $4f^7$ to excited $4f65d1$ states. The excitation for Eu^{3+} may take the form of characteristic intra- $4f$ transitions and additional pathways associated with charge-transfer or host-related. These spectra should be interpreted with caution. But an excitation peak does not always correspond to one micro mechanism and the emission spectrum may be influenced by instrumental response and reabsorption. Comparisons should, therefore, include the wavelength of the excitation, the slit width, the integration time, the detector setting, and if the spectra were corrected for instrument response.

5.6 Concentration quenching

As concentration of the activator increases, at first it may increase the number of absorbing centres, and further enhance the total emission. However, at high enough concentrations energy migration between activators can make it easier to get to the non-radiative loss centres. Such behaviour is referred to as concentration quenching. Quenching is not a constant for all materials and depends on the concentration. It is dependent on lattice type, on distribution of the activators, on the quantity of defects, on the conditions of excitation, on the criterion for optimality. Concentration quenching studied by the series of samples prepared in similar conditions. Measurements should include corrected emission spectra, and quantum yield and lifetime data (if available). Other factors such as changes in phase composition, particle scattering, sample packing or absorption can also lead to a decrease in peak intensity. It is possible that the concentration that optimizes measured intensity is not the concentration that maximizes the internal

quantum efficiency. The results of this should be separated from other experimental results and literature comparisons.

5.7 Thermal quenching and temperature-dependent emission

The increase of temperature causes a higher probability of non-radiative relaxation than radiative emission, resulting in thermal quenching. Thermal activation of non-radiative pathways can cause a decrease in the emission intensity for Eu^{2+} , and in some hosts, a shift in the emission-band shape or position. These temperature dependent measurements are relevant to SCL as phosphors can be used in environments that are different from those in which they are measured at room temperature in a laboratory. The energy of the excited states, lattice vibrations, defects and energy transfer processes of the activator may influence thermal behaviour. A good study should report the emission over a certain range of temperatures and the conditions under which the emission was studied (excitation conditions and sample temperature). Thermal-quenching parameters should be obtained from a model that has been explicitly stated and, in turn, applied to measured data, not deduced from limited and unreported or incomparable measurements. Thermal stability is also different from chemical stability. A material can undergo significant reduction in emission during heating without changing its crystal structure, or a structural change may occur that impact the optical performance during heating. These two are relevant in applications to devices.

6. Defects and Persistent Luminescence

The ability to distinguish between prompt and persistent luminescence. The capability to differentiate prompt and persistent luminescence. Prompt photoluminescence is measured during or shortly after the excitation of a material, depending on the instrument and experimental procedure. Persistent luminescence is the light that continues to be emitted once the light source is no longer present. Persistent emission is generally more complicated than radiative transitions and requires extra processes which will slow down the return of the excitation energy to the emitting centre. The role of the activator as a radiative centre, and the effect of defects and co-dopants on the storage and release of energy may occur in Eu^{2+} -activated calcium aluminates. In the case of persistent phosphors, the co-dopants Nd^{3+} and Dy^{3+} have been investigated in calcium aluminate. They cannot be assumed to be the same for different compositions and host and defect structures. Afterglow times are dependent on the trap depth distribution, the number of trapped charge carriers, recombination pathways and temperature. The afterglow observed is therefore not sufficiently accounted for by activator emission.

6.1 Formation of traps and release of the carriers

Excitation can cause the electrons or holes to move to defect or co-dopant levels. These carriers can be trapped for some time and subsequently released by thermal activation or other methods. The recombination can then transfer the energy to the activator that emits a photon. The depth of the trap affects the time scale of the trapped carriers release. The shallow traps might be emptied quickly, and the deep traps might be emptied too slowly in practice. A useful persistent phosphor must thus have a trap distribution to suit the application and the operating temperature. The trap mechanism shouldn't be simplified to the concept that if more defects are created, the better the persistence will be. Defects can act as useful storage centres, but they can also act as non-radiative recombination centres or be a part of a problem for charge transport. The influence of them is effected by defect type, concentration, energy level and with activator.

6.2 Role of co-doping

Co-doping is a common method of tuning the optical and defect characteristics of phosphors. The most common emitting centre in calcium aluminate is Eu^{2+} and other rare-earth ions can also affect the trapping and afterglow properties. The studies of $\text{CaAl}_2\text{O}_4^{2+}, \text{Nd}^{3+}$ have focused on the long-persistence emission and those of $\text{Eu}^{2+}, \text{Dy}^{3+}$, and Nd^{3+} have examined the effect of co-dopants on afterglow properties. These studies illustrate the importance of defect engineering, but the effect of each co-dopant is reliant on the host and the conditions used for the preparation. A well-controlled study should include an undoped host, a composition containing only Eu, and appropriate co-doped compositions, all made by similar methods. Afterglow changes thereafter should be evaluated in relation to phase composition, emission spectra, decay behaviour, and (if possible) trap related measurements.

6.3 Characterization of persistence

The following should be recorded in afterglow measurements: the excitation source, excitation time, excitation intensity, time between excitation and measurement, detector sensitivity, and temperature. A decay curve should be presented over a broad enough time window to display the behaviour of interest. Persistent luminescence is occasionally approximated by an exponential function. However, it is not always possible to describe a system with a distribution of traps with a single exponential. The selection of models should, therefore, be explained and the parameters estimated in the model should not be assumed to be direct measurements of the respective trap depths. Trapped carriers can also be determined by the light emitted from a sample after it is heated after irradiation, called thermoluminescence. It needs explicit experimental protocol and appropriate model for interpretation. Other methods such as temperature dependent spectroscopy and electron paramagnetic resonance can be used to aid in the identification of relevant defects or trapped charge states. Characterization Techniques and Reporting Standards.

7. X-ray diffraction

Among the main methods for analysing the crystalline phases in calcium aluminate phosphors, X-ray diffraction (XRD) is one of the most important ones. The obtained diffraction pattern can be compared to a suitable reference pattern to determine the main crystalline phases and to study the structure changes that may have occurred due to doping or thermal treatment. Use the entire diffraction spectrum, if available, to identify the phase; do not take a single match peak. When the secondary phases present at low concentration or when the peaks from these phases are in the same region as the dominant phase, the identification can be challenging. If there is sufficient quality of data, and the structural models and phase information are not too complex, then Rietveld refinement may be useful. When the lattice parameters and/or phase fractions are refined, they should be provided with suitable uncertainties and/or indicators of the refinement. A small amount of dopant can cause a peak shift which is not easily distinguishable, and since the shift is not observed does not indicate that europium has not "entered the lattice."

7.1 Electron microscopy and elemental analysis

The scanning electron microscope can give you information on particle shape, agglomeration, particle surface morphology, and approximate particle sizes. At the finer scale, transmission electron microscopy techniques can be used to show more detail of structure, and energy-dispersive X-ray spectroscopy can be used to help evaluate the distribution of elements. Interpretation of microscopy images should be considered with caution. The apparent size of a particle in an SEM image may be composed of a number of small crystallites, and the size of the particles measured by SEM may not be identical to the crystallite size determined from diffraction analysis. Elemental mapping can also be used to generate evidence of compositional uniformity at spatial scales that can be achieved with the instrument. It cannot, alone, prove the oxidation state of europium and does not provide evidence that all europium ions fill calcium sites.

7.2 Photoluminescence spectroscopy

The evaluation of excitation and emission behaviour is the core of photoluminescence spectroscopy. As a minimum, the wavelength of excitation, the range of emission, the temperature of measurement and the instrument settings should be reported. Researchers should specify whether or not the spectrum is normalized and the normalization procedure if comparing spectra. Normalized spectra are used for comparison of the shape of the spectra but not for a direct comparison of the absolute emission intensity. The measurement of absolute or relative quantum yield should be made by an appropriate calibrated

procedure. When the goal is to evaluate the efficiency of the material when used in devices, absorption, emission and thermal behaviour should be taken into account.

7.3 Lifetime measurements

The use of time-resolved photoluminescence may be useful to separate emissive centres and to assess variations in radiative or non-radiative processes. The meaning of a decay curve is different for each emitting species, depending on the excitation conditions, the time resolution, and whether more than one population of the species is emitting. A reported lifetime should be followed by an indication of the method used for measuring it and the type of fitting. When a curve exhibits multi-exponential decay, this can be interpreted as the presence of more than one environment or relaxation pathways, however, this requires evidence which goes beyond the mathematical fitting.

7.4 Valence-sensitive measurements

It is necessary to know the oxidation state of europium when comparing the emission of Eu^{2+} and Eu^{3+} . X-ray absorption near-edge structure (NEXAFS) spectroscopy can give information on oxidation state and local electronic structure. Additional, complementary spectroscopic techniques such as electron paramagnetic resonance, X-ray photoelectron spectroscopy may also be useful as long as they can be applied and are potentially sensitive. X-ray photoelectron spectroscopy is surface sensitive, and the oxidation state measured at the surface may not be representative of the bulk. Likewise, the relative Eu(II) and Eu(III) populations may not be completely estimated by optical emission. Interpretations based on multiple independent measurements of a spectrum are more secure than one spectral assignment if it is suggested that mixed-valence behaviour occurs.

Table 2

Recommended Characterization Framework for Europium-Doped Calcium Aluminate Phosphors

Research question	Recommended method	Primary information	Important limitation
Which crystalline phases are present?	XRD	Phase identification and structural information	Minor or overlapping phases may remain undetected
How does the powder morphology change?	SEM and, where appropriate, TEM	Particle morphology and finer structural features	Imaging alone does not establish bulk phase purity



Is the composition consistent with the intended recipe?	Elemental analysis and suitable chemical analysis	Elemental composition and distribution	Elemental data alone do not establish oxidation state
Which wavelengths excite the phosphor?	Excitation spectroscopy	Excitation pathways associated with selected emission	Interpretation depends on the monitored emission wavelength
What wavelengths are emitted?	Emission spectroscopy	Spectral shape and emission features	Intensity depends on measurement conditions
What is the emission efficiency?	Absolute quantum-yield measurement	Fraction of absorbed photons emitted	Requires a suitable calibrated measurement protocol
What is the emitting-state lifetime?	Time-resolved photoluminescence	Decay behaviour and lifetime parameters	Model-dependent when several populations contribute
Which europium oxidation states are present?	XANES and complementary spectroscopy	Evidence concerning oxidation state and electronic structure	Sensitivity and sampling volume depend on technique
How does temperature affect emission?	Temperature-dependent photoluminescence	Thermal quenching and spectral changes	Requires controlled and documented sample temperature
How long does emission persist after excitation?	Time-resolved afterglow measurement	Decay behaviour after excitation ceases	Depends on excitation history and detector sensitivity

Note. The table is a proposed methodological framework, not a record of measurements conducted for this review.

8. Applications in Solid-State Lighting

8.1 Blue-emitting phosphors

The Eu^{2+} -activated calcium aluminates are of interest as they emit light in the blue region, which can be used with other spectral components in lighting systems. The choice of a specific composition is determined by its suitability in terms of excitation spectrum, emission wavelength, quantum yield, thermal stability and

compatibility of the chosen LED chip. The blue band of emission should not be taken as sufficient for a lighting application without careful consideration. It is only useful if the total spectral output is available and the optics of the device are designed to generate the required output. Colour coordinates, luminous efficacy, colour rendering and operating-temperature performance measurement may be necessary at the device level. $\text{CaAl}_2\text{O}_4^{2+}$ has been studied as a blue-emitting host material, but it needs to be compared with other phosphors under standard measurement conditions.

8.2 Red-emitting phosphors

The emission of red or orange-red color can be achieved by the use of Eu^{3+} containing calcium aluminates due to the intra-4f transitions. This emission can be useful in spectral balancing in white-light systems or for applications where red luminescence is desired. These phosphors are appropriate for use depending on the intensity and distribution of the emission lines they produce, their ability to be excited, and their thermal properties. As a general rule, a material that fluoresces well with near UV excitation may not be suitable for a device which excites predominantly in another spectral region. Also, high colour rendering does not guarantee high luminous efficiency, and high luminous efficiency does not necessarily guarantee narrow-line red emission. The properties are based on the combined spectral output and visual response of the system.

8.3 White-light generation

A white light can be created using a number of spectral approaches: for example, a blue-chip excitation of down-conversion phosphors or a near-ultraviolet excitation of multiple phosphors, or a combination of several different emitting centres. When the excitation and emission properties of europium-doped calcium aluminates are suitable for the requirements of the design, it is possible to use them in these systems. It is important to note however, that there is a difference between the “potential” of a material for solid-state lighting and the “performance” of a working device. The efficiency of the LED that contains this powder in its composition, the colour stability, and the lifetime cannot be determined by a powder-level photoluminescence spectrum. The spectral power distribution, correlated colour temperature, colour rendering index, luminous efficacy, thermal management, encapsulant compatibility and long term stability should be taken into account in the device-level evaluation.

8.4 Lighting and emergency lighting: permanent

There has also been some work on persistent calcium aluminate phosphors for use in applications where emission is desired following the removal of the excitation source. These materials can be used for

emergency marking, low light emitting applications, or other delayed emission applications. These applications place requirements on the application that are different from typical LED down-conversion. A persistent phosphor is evaluated based on its charging efficiency, initial brightness, decay curve, performance at relevant temperatures and reproducibility of performance over repeated light excitation cycles. But a practical suitability does not follow solely from the very existence of an afterglow. Performance should be evaluated for a specific type of excitation and in relation to the illumination needs of the intended use.

8.5 Practical issues related to device integration

The behavior of powder phosphors might differ when used in devices. The observed performance can change due to scattering of particles, refractive index mismatch, encapsulation, exposure to moisture, or transfer of heat. Agglomeration may also have an impact on dispersion and optical uniformity. Research should therefore be extended from phase and spectroscopic characterization to testing in a realistic optical configuration, for this reason. The performance of the material needs to be compared to relevant alternatives with the same excitation and operating conditions.

9. Critical Discussion

The properties of synthesized materials and their optical performance are linked. The optical properties of synthesized materials are related to their properties. From the literature researched, it is evident that the synthesis conditions affect the PL in several interrelated ways. The relative amounts of the various calcium aluminate phases generated depend on precursor stoichiometry, the amount of crystallinity and morphology depend on the reaction conditions, the oxidation state of the europium ion and the defect chemistry depends on the atmosphere, and the concentration of the dopant will change the probability of energy transfer between the activators. These variables should not be considered as independent. For instance, the crystallinity can be enhanced by raising the annealing temperature, but the particle size will be enlarged and the distribution of the valence of Eu will be altered. Therefore an increase or decrease in emission strength cannot be attributed solely to crystallinity, without further evidence. Likewise, a modification of the fuel to oxidizer ratio in the combustion synthesis process can affect the porosity, local temperature, phase composition and defect populations all at once. A good study should involve identification of those factors that are manipulated and, if possible, a controlled experimental design that will isolate their effects.

9.1 Europium Oxidation State is important

The difference between Eu^{2+} and Eu^{3+} is at the heart of the interpretation of calcium aluminate photoluminescence. The broad-band Eu^{2+} emission and the line-like Eu^{3+} emission are due to different electronic transitions and they are differently sensitive to the surrounding lattice. Processing conditions can be used to induce a Eu^{2+} precursor into a material, with the result being a material that contains Eu^{2+} . Oxidizing treatment, on the other hand, might lead to an increased trivalent fraction. Thus the final optical response is a consequence of the chemical history of the sample and not only of the oxidation state of the starting reagent. Precursor oxidation state, treatment atmosphere, and annealing conditions as well as evidence for determining the final europium valence should be reported in future work. For problems in which mixed valence is suspected, the relative importance should be determined with appropriate complementary techniques. There are difficulties in comparing published results. Comparing published results presents some difficulties. One of the difficulties with phosphor research reviews is the variety of measurement conditions and reporting used. Other studies have concentrated on peak emission intensity, integrated intensity, or quantum yield or afterglow duration. These endpoints are meant to answer different questions. This is also true when spectra are normalized to their max. Normalization allows for comparison of the shape of the spectra, but does not preserve information about the intensity. Normalized spectra should thus not be used for the sole purpose of ranking materials by brightness. Comparisons are also not possible if the host phase, the excitation wavelength, the packing of the sample, or the instrumental conditions are changed. Data in this form would be suitable for a meaningful quantitative synthesis with easily comparable data, including information on uncertainties and experimental conditions. When these requirements are lacking, qualitative synthesis is more defensible than a pooled numerical ranking.

9.2 Research gaps

The literature yields some research priorities. The first is the need to judge the phase purity and valence of europium together. To interpret a spectrum, it is essential to determine if the sample contains the desired host phase and if the proposed emitting centre is verified with suitable evidence. Second, it is important for more studies to report the absolute quantum yield and the temperature dependent emission to the conventional spectra. These measurements would help in more meaningful consideration of actual lighting performance. Third, the same target composition and processing conditions should be used for synthesis comparisons. It would be very interesting to make direct comparisons between combustion and solid-state and sol-gel methods, especially if the same characterisation protocol was used for the final materials. Fourth, it is necessary to have more experimental support for defect-related mechanisms. Decay curves,

thermoluminescence (where applicable), or other appropriate measurements should be used to investigate persistent emission, rather than its being inferred from co-dopants alone. Last, but not least, there will be more focus on the link between powder properties and device performance. Before any claims of practical superiority, one needs to assess the various aspects of whether the material is “spectral compatible”, “thermally stable”, “optically extractable” and “reliable” for long term use.

9.3 Limitation of the present review

This review is not systematic. Does not provide a thorough database search, formal screening diagram, quantitative risk-of-bias evaluation or meta-analysis. The compositions used in the studies, the methods for synthesizing them, and the optical measurement conditions are not the same, making it difficult to compare the numbers directly. The review also is not a report on additional experimental work. No sample was prepared, no new diffraction patterns, emission spectra were collected, no quantum-yield measurements were performed and no lifetime data was collected. The conceptual tables and proposed figure are not intended to reflect experiment but to summarise and organize knowledge and to provide a guide for future developments. The final reference list should be double-checked with the original publications before submission to the journal, including author order, publication year, journal information, page ranges, article numbers, and DOI information. For a formal systematic review, a separate search and screening process would be required for the claim.

10. Suggestions for further studies.

A starting point for future investigations should be the optical function of the material which is desired. If the phosphor is used for blue emission under LED excitation, the optimization strategy is different from that of a phosphor with a red emission or a long afterglow. The study for Eu^{2+} -activated compositions should be directed toward the control of phase formation, stabilization of valence state, high efficiency of luminescent radiation and thermal quenching. For Eu^{3+} activated compositions, the site symmetry, transition intensities, excitation compatibility, and the effect of compensating defects should be considered. It would be useful to experiment with different dopant concentrations, different annealing gases, and annealing temperatures, with all other preparation parameters being kept as similar as possible. To establish relationships between processing and performance, measurement of phase composition and europium valence along with optical properties must be measured. The uncertainties of the researchers should be reported and measurements should be repeated if possible. If several batches of synthesis have been made, assess batch-to-batch variation, don't assume that one batch is representative of the entire composition. If quantitative modelling is done using data, the chosen model, modelling procedure and estimates of uncertainty should be clearly

reported. If the phosphorescence is long lasting, the studies should include the source of the charging, the length of the charging, the level of irradiance, the delay before measuring, the temperature, and the decay interval. These details are necessary for making comparisons of afterglow performance in studies. Lastly, potential compositions should be tried in representative devices. Such evaluation would help to determine if the emission advantage of the material can be maintained at scale, and if it provides any real benefit over existing phosphor systems.

11. Conclusion

The europium-doped calcium aluminate phosphors are a class of luminescent materials with very versatile properties which depend on the host composition, the oxidation state of europium, the local crystallographic environment, the synthesis conditions, and the defect chemistry. They do not have an optical behaviour that can be explained with an adequate description by the dopant concentration, only by the nominal chemical composition. Eu^{2+} -activated calcium aluminates are of interest for broad-band blue emission and persistent luminescence while Eu^{3+} activated compositions may have a characteristic red or orange-red emission. These differences are due to their electronic configuration and transition processes. Concurrently, the emission wavelength, the shape of the emission spectrum and the non-radiative relaxation channels are affected by the host-phase formation and by the local coordination. There are different methods to material preparation, such as solid-state reaction, solution combustion, sol-gel processing, and other solution-based techniques. Both have pros and cons with respect to precursor homogeneity and processing temperature, as well as the formation of the phase, the morphology, and control of europium valence. The optical response desired depends on the maintenance and/or generation of Eu^{2+} , and this requires post-synthesis annealing and atmosphere control of the final material. The literature also focuses on the differences between prompt and persistent luminescence. While both types of transitions involve radiation, the persistent emission is delayed energy release, and is affected by defect-related trapping and recombination processes. Thus, an appropriate characterization must be consistent with the property under investigation. Complementary structural, compositional, optical and valence sensitive measurements are required to make a reliable assessment of these materials. Researchers should not use the peak intensity as an indicator of quantum yield, normalized spectra as an absolute brightness measure, or powder level emission as an indicator of device level emission. In conclusion, europium-doped calcium aluminates are still significant research topics regarding the structure-property relationship in oxide phosphors. The development of the practical applications of solid-state lighting will depend on the reproducible synthesis, increased support for proposed

mechanisms of luminescence, standardized optical characterization, and validation under realistic operating conditions.

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