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Structural and Optical Investigations of Rare Earth Doped Nanophosphors for Solid-State Lighting Applications

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Abstract: In this study, rare earth doped phosphors prepared by controlled solid-state reaction technique are examined for the structural and optical characterization. It was further characterized that the resulting nanostructures exhibited a pure crystalline phase with nanometer size crystallite, near spherical morphology with little agglomeration as evident from the X-ray diffraction analysis (XRD) and SEM and TEM micrographs. UV-Vis absorption measurements had shown a small decrease in the optical band gap upon increasing the dopant concentration due to defect-mediated localized states. Photoluminescence (PL) measurements showed typical sharp lines for the rare earth ions: $Eu^{3}+$ doped phosphor displayed strong red emission (^$5D_0 \rightarrow$ ^$7F_2$), $Tb^{3}+$ doped sample showed strong green emission (^$5D_4 \rightarrow$ ^$7F_5$) and for $Dy^{3}+$ doped sample the sample emitted bluish-white light through coexistence of blue and yellow transitions. The PL emission was enhanced with increasing dopant concentration up to an optimal value (~3–5 mol%) after which concentration quenching led to a decrease in luminescence efficiency as a result of non-radiative energy transfer. Lifetime measurements corroborated this behaviour. The CIE chromaticity of Eu 3+ and Tb 3+ doped phosphors had pointed out the utilization of these phosphors as red and green components for display technology, respectively, while Dy 3+ doped phosphors have potential application in white light-emitting diode (w-LED). These results demonstrate the tunability of rare earth doped phosphors for structural and optical properties, emphasizing their potential in the next-generation optoelectronic and solid-state lighting device applications.

Keywords--Rare earth doped phosphors, Photoluminescence, Band gap tuning, Concentration quenching, CIE chromaticity, Solid-state lighting, Nanophosphors

I. Introduction

In the last few years, the rare-earth (RE)–doped phosphors, which possess fascinating optical properties and have extensive applications in lighting, displays, lasers, sensors, and biomedical imaging, have attracted considerable attention. The characteristic luminescence of rare-earth ions stems from weakly screened 4f ele ctronic shell due the lanthanide contraction with respect to the outer 5s and 5p orbitals. This shield effect gives extremely well-defined and sharp emission lines, high colour purity, long afterglow lifetimes, and high photo stability, so RE-doped phosphors are better than most of the traditional luminescence materials. The properties of these phosphors such as photoluminescence excitation and emission spectra, quantum efficiency, and energy transfer kinetics depend on the host lattice, the concentration of dopant ion, as well as preparation condition. Optical characterisation clarifies the basic principles of radiative and non-radiative transitions, leading to the optimisation of emission intensity, wavelength tunability and thermal robustness. These studies are necessary for engineering materials that can be used for solid-state lighting (SSL) (such as, for example, white light emitting diodes (LEDs)), which need to have phosphors that are not only efficient, but also stable, and environmentally friendly [1].

The structure of host lattice are also crucial in the understanding of activities of RE-doped phosphors. Methods including X-ray diffraction (XRD) can be used to gather data related to crystal phase, cell parameters, crystallite sizes as well as scanning and transmission electron microscopy (SEM and TEM) for the particle morphology, particle size, and microstructural homogeneity. In addition, the EDS and similar analytical techniques can be used to measure elemental composition and dopant distribution, the information that is needed for a relationship of the microstructure and luminescence behaviour. The structural analysis is relevant not only for the validation for successful RE ions incorporation in the host matrix, but also to search for defects, secondary phases or stress/strain effects that could be responsible of optical performance. An optical–structural approach provides a full elucidation on the correlation between the material structure and photoluminescence properties. Through carefully examining these factors, scientists have the capability to optimize host–dopant interactions, govern the energy transfer mechanism and ultimately increase the efficiency of the material.

Research in this field is critical for the development of new-generation high-efficiency, thermally and spectrally stable phosphors. In recent years, there has been extensive research on RE-doped phosphors, mainly due to the increasing need for sustainable lighting and display technologies offering high performance. Improvements in synthesis methods, such as sol–gel, hydrothermal, and combustion routes, have resulted in better control of particle size, shape, size distribution, and crystallinity, resulting in enhanced optical properties. Such experimental studies allow for the possibility of an en" lightened design toward materials that fulfil strict demands set by the today's photonic and optoelectronic applications [2].

1.1 Optical Studies of Rare-Earth Doped Phosphors

Optical examination of rare-earth (RE)-doped phosphor materials is necessary in investigating their luminescence characteristics, and in optimizing their performance for lighting, display and photonic purposes. This unique optical features of RE ions occur due to intra-4f electronic transitions, which are relatively well protected by the outer 5s and 5p orbitals. This shielding reduces the effect of the surrounding crystal field, which leads to sharp emission peaks, long fluorescent times and a high colour purity. One of the main points of interest in optical studies is the analysis of PL excitation and emission spectroscopy, showing the energy levels that take part in radiative transitions. Quantum efficiency determination is useful to estimate the fraction of absorbed energy converted to emitted light, and lifetime studies are useful to probe the stability of excited states. Furthermore, the optical characterization usually comprises temperature dependent PL measurements to study the thermal quenching behaviour and stability under operation.

Energy transfer processes, e.g. sensitizer-to-activator transfer and cross-relaxation, are likewise essential to adjust emission colour and intensity. These processes are very sensitive to host lattice, dopant concentration, and co-dopant type. For instance, too high dopant concentration may cause concentration quenching and a decrease in emission efficiency. Sophisticated spectroscopic tools, including time-dependent and diffuse reflectance spectra measurements, allow detailed study of electronic transitions and optical bandgaps. These studies lend a detailed insight into host–dopant interactions and their impact on luminescent characteristics, which lies outside the scope of this discussion. Through a systematic optical examination of both synthesis parameters and compositional design of RE-doped phosphors, researchers can achieve RE doped phosphors with improved brightness, colour tunability and thermal stability. Such knowledge is of significant importance for the design of high-performance phosphors for solid-state lighting, laser devices, and optical sensorics [3].

1.2 Structural Studies of Rare-Earth Doped Phosphors

Among others, structural investigation of rare-earth (RE)–doped phosphor materials is very essential to interpret the crystal structure, dopant incorporation and microstructural details which are directly responsible for the luminescence performance. The host lattice acts as the matrix in which the RE ions are doped and the crystal structure of the host material will determine the symmetry and the local environment of the dopant sites and hence also the nature of the optical transitions. The crystal phase, lattice parameter, and degree of crystallinity are determined primarily by XRD. Relatively small variations in the structure as a function of RE ion substitution can be quantified by Rietveld refinement of the data, indicating successful doping and screening for any secondary phases that may detrimentally affect luminescent properties. Lattice strain or distortion due to ionic radius mismatching between the RE dopants and host cations could affect energy transfer and emission efficiency [4].

The scanning and transmission electron microscopy (SEM and TEM) from microstructural investigation reveals particle size, morphology, and syn texture. Rigorous size distribution and regular shape are also required in order to enable the particles to display consistent optical responses or to have good dispersion in application media. HRTEM images show the lattice fringes and defects, and the SAED patterns further clarify crystallinity and phase purity. Elemental analysis via energy dispersive X-ray (EDX) or wavelength dispersive (WD) techniques confirms the dopant and its even distribution within the host. This level of homogeneity precludes concentration differences that might lead to local quenching or separation. Being able to correlate microstructure with optical properties provides insight into why some phosphors are applicable for a given application, while others are not. Absorption, Emission, and Thermal Stability The crystallite size, defect density, and surface states have a strong influence on the absorption, emission and thermal stability. By tuning the synthesis condition to obtain its high crystallinity, phase purity, and controlled morphology, structural studies provide the insight into high-performance phosphors for advanced optoelectronic devices [5].

1.3 Unique Luminescence Mechanism

Due to the intra-configurational transitions of partially occupied 4f electronic states, the rare-earth (RE)-doped phosphors exhibit unique luminescence. These 4f electrons remain relatively shielded from the ligands present in the crystal, because the filled outer 5s and 5p orbitals help to neutralize the charge that surrounds the inner electrons, so 4f electrons suffer little influence from any host lattice. According to consequence, optical transitions are weakly dependent of local environment, there are sharp well resolved emission lines of high spectral purity. Such a shielding effect contributes to high photostability, long emission lifetimes, and stable performance in different host matrices, making RE-doped phosphors promising materials for the precision lighting, display technology and photonic industry [6].

1.4 Structural Property Studies

The structure characterization of rare-earth (RE)–doped phosphors is of great importance to the correlation between microstructures and the performance of luminescence. Techniques such as X-ray diffraction (XRD) are used to determine crystalline phase, lattice parameters and relative degree of crystallinity to prevent re ions are inserted in the host lattice without the creation of undesirable secondary phase. The surface morphologies and particle size distributions, which are important factors affecting the light-scattering effects and the emission uniformity, have been analyzed by SEM characterization. The use of HRTEM and TEM allows for lattice fringes or crystallite size vertices or defect zone occurrences to be identified at the nano scale, providing insights into structural integrity. Moreover, energy dispersive X-ray spectroscopy (EDS) contrastingly verifies the elemental compositions and dopant doping on distribution of RE ions and the even distribution of RE ions in the host matrix. Through relating these structural parameters phase purity, shape, defect density, and dopant uniformity—with the photoluminescence properties, the growth conditions can be fine-tuned to improve the emission intensity, the colour consistency, and thermal robustness [7-8].

1.5 Integration of Optical and Structural Insights

An in-depth study of rare-earth (RE)–doped phosphors must involve an optical and structural analysis together to obtain a clear relationship between the material microstructure and photoluminescence properties. Structure-related characterization offers fundamental information about crystallographic phase, lattice symmetry, particle morphology, defect states, and dopant distribution, with optical characterization involving emission intensity, spectral features, quantum efficiency, and lifetime performance. Through the correlation of these data, it is possible to observe the impact of structural parameters such as crystallite size, defect density, and dopant site occupancy on radiative and non-radiative transitions. This dual approach allows the tuning of host–dopant interactions, which is necessary to optimise energy transfer mechanisms, reduce quenching, and obtain accurate control on the final colour. Moreover, the combination of optical–structural effect promotes the design of phosphors with superior photoluminescence efficiency, long-term thermal stability, and spectral stability in wide operating conditions. Such a synergy is essential for the development of the next-generation phosphors to satisfy high demands of advanced lighting systems and display and photonic devices [9-10].

1.6 Advances in Synthesis Techniques

The synthetic procedure has a great impact on the luminescent performance of the RE-doped phosphors because the particle size, morphology, crystalline form, and defect amount are closely related to the luminescent efficiency and stability of phosphors. Recent development in the synthesis process including sol–gel, hydrothermal, and combustion processes allowed the control of these structural parameters at will-term. The uniformity of dopant distribution in the host lattice is achieved by sol–gel, which also provides a low-temperature processing and good homogeneity. Hydrothermal approach is also known for the possibility of preparing nice crystallized particles with controllable morphologies under relatively soft conditions and sometimes even avoiding post annealing. The combustion methods with low-cost and easy process offer quick and energy-saving synthesis thus giving a very short reaction time to obtain highly crystalline powders. Such approaches do also enable the control of the particle size on the particle scale (nanometer to micrometer) that is important in view of optimizing the light scattering, surface and emission properties. By tuning the synthesis parameters including pH, temperature, reaction time, precursor concentration, researchers can design phosphors with a higher luminescent intensity, better colour luminescent stability and thermal stability. The advances are critical in the realization of the next era of photonic optoelectronic devices, such as high-performance LEDs, display systems, laser, and optical sensors [11].

II. Reviews of literature

Luo et al. (2020) addressed that optical transition properties of trivalent rare earth ions in transparent hosts are commonly studied in the Judd–Ofelt theory within a standard calculation method based on the analysis of absorption spectra. They had drawn attention to the fact that for powder and film material, such properties cannot be determined directly due to the difficulty in obtaining absolute absorption spectra. To tackle this matter, they had suggested an alternative way to estimate Judd–Ofelt parameters in trivalent RE ion-doped materials in different morphological and shaped forms from the decay fluorescence values, which were in between the radiative transition rates and the Judd–Ofelt parameters. As an application, they have applied the method to the Judd–Ofelt parameters of Er^{3+} in $NaYF_4$, and their results are consistent with those derived from orthodox procedures. The same study had also shown that their proposed method was feasible and practically applicable for the estimation of the optical transition properties of trivalent RE ions in non-transparent hosts if fluorescence decay data were available.

Zhou et al. (2020), optical temperature sensing has attracted considerable attention because of its unique superiority, and the majority of specific research groups have developed optical thermometers with thermally coupled levels (TCLs) of rare earth ions however lacked both high sensitivity and strong signal discriminability. To solve this drawback, they had suggested a novel dual-activator scheme, in which the major difficulty was that the two activators were not always activatable at the same time. They prepared Mn4+/Eu3+ co-doped double-perovskite NaLaMgWO6 (NLMW) phosphors using a theory of site-preference occupancy and investigated their temperature-dependent luminescence (303-523 K) by comparing their luminescent properties with those of NLMW: Mn4+.1≤ Eu3+ The results indicated that Mn4+ and Eu3+ occupied different cation sites, and while both of them could lead the red emission, Mn4+ demonstrated much higher fluorescence intensity than Eu3+ with the variation of temperature. It was observed that Mn4+ luminescence decreased more quickly with increasing temperature than Eu3+; thus, Mn4+ could be a temperature sensor and Eu3+ as a reference, and the calibration plot of the temperature as a function of the intensity ratio (FIR) was found to be highly sensitive. They had also estimated the activation energy for thermal quench for Eu3+ and Mn4+ as 1.83 and 0.367 eV, respectively. A follow-up study found that the maximum relative and absolute sensitivities were 0.86% K−1 at 523 K and 3.02% K−1 at 363 K, respectively, which were better than most of the TCL-based optical materials [238]. It therefore concluded that the prepared phosphor could be potentially utilized for the dual luminescent centers self-referencing optical thermometry.

Song et al. (2020) reported that rare-earth ion-doped phosphors were widely employed as temperature sensors due to their strong luminescence properties, however, the high cost and scarcity of rare-earth elements motivated researchers to search for new luminescent materials with transition group elements, which are relatively less expensive and easily available. A phosphor system doped with rare-earth ions and transition metals has been designed in the present work for optical temperature sensing. It was also pointed out that the Mn4+-doped phosphors have attracted much attention for this strong DRE, and La2LiSbO6 was thought to be an efficient host lattice of Mn4+ and Eu3+ because of its unique crystal structure. Abstract: A series of La2LiSbO6: Mn4+, Eu3+ single-doped, and La2LiSbO6: Eu3+/Mn4+ co-doped phosphors were prepared and fractional studied on crystal phases and optical properties. The authors had done a specific study of temperature dependent fluorescence of La2LiSbO6: Eu3+, Mn4+ in the temperature region of 303K-523K which are explained below. It was discovered that the fluorescence intensity of Mn4+ was more susceptible to thermal quenching than Eu3+; thus, the fluorescence intensity ratio (FIR) between Eu3+ and Mn4+ was able to be used, therefore, in temperature detection. The maximum relative sensitivity was 0.891% K−1 at 523 K and the absolute sensitivity at this temperature reached 0.000264 K−1. The research determined that La2LiSbO6:Eu3+/Mn4+ phosphors had a temperature detection high sensitivity and were promising for advanced temperature sensing applications.

Katyayan and Agrawal (2020) had investigated the thermal and optical characteristics of CaSiO3:Eu2+, Er3+, BaSiO3:Eu2+, Er3+, and SrSiO3:Eu2+, Er3+ phosphor prepared through molten salt synthesis method. They were prepared by using different doping contents of Eu2+ and Er3+ ions (0-1 mol%) and their structural, optical, and thermal properties were studied. Their powder X-ray diffraction analyses showed that the CaSiO3:Eu2+, Er3+ has a triclinic structure, BaSiO3:Eu2+, Er3+ an orthorhombic structure, and SrSiO3:Eu2+, Er3+ a monoclinic structure with nice homogeneity and phase purity. Through field emission scanning electron microscopy and transmission electron microscopy, irregularity in particle shape, differences in size and heat treatment-induced aggregation had been demonstrated by previously conducted morphological and topographical evaluations. It was also noticed that the as-prepared violet phosphors were thermally stable and essential weight loss was seen between room temperature and 700 degreesC by thermogravimetric analysis. The deep trapping of UV-,γ-irradiated phosphors with the second- order kinetics according to the thermoluminescent spectra confirmed based deep level traps, and determination of the trap depth revealed the existence of the electron trapping which accommodated at the deep trap center with the large activation energy (~3 eV). It observed that the co-doping of Eu2+ and Er3+ as pair of conjugate rare earth increases defects in host lattice which was responsible for favoring the trapping mechanism. Furthermore, gamma-irradiated phosphor exhibited a greater thermoluminescent intensity, more effective deep trap occupation, and more stable fading over that of UV-irradiated phosphors.

Archana, Rajendran [41] in 2021 also reported that rare earth ions activated semiconductor phosphors were the preferred luminescent materials for optical display. They had described the luminescent behavior of the Ce^{3+} and Eu^{3+} ions doped ZnS prepared by solid-state reaction. Structural, optical and morphological properties of these materials were examined using X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FT-IR), Field Emission Scanning Electron Microscope (FE-SEM), Energy Dispersive Spectroscopy (EDS), UV–Vis and photoluminescence (PL) measurements. The XRD analysis had indicated that the prepared samples possessed a hexagonal wurtzite structure and the FTIR spectroscopy had shown some vibrational bands related to various functional groups. The band gap energy and absorption edge were estimatedby UV–Vis spectrum, EDS analysis has been checked for the purity of the material. The PL studies had also indicated that rare earth-doped materials emitted the typical emission due to radiative transitions related to the third state 3^{+} of energy levels. The calculated CIE coordinates indicate that ZnS: Ce3+ and ZnS: Eu3+ are potential phosphors for optical display device.

Gupta, I., Singh, S., Bhagwan, S., Singh, D. (2021) demonstrated the technology of luminescent Materials has gained remarkably from considerable progress of research and development, where the solid inorganic luminescent materials or solid-state phosphors have been known as the optoelectronic materials of the 21st century due to their good efficiency, eco-friendly and also used for extended display applications. It was reported that inorganic phosphors had been extensively investigated to replace low-voltage light source, as a result of the increasing energy consumption throughout the world. As the authors pointed out, modern white light-emitting diodes (WLEDs) have gradually replaced the incandescent and fluorescent lamps containing mercury due to the long lifetime, low power consumption, reliability and high luminous efficiency. The review had focussed preparation, luminescence and applications of rare-earth (RE) activated phosphor materials for solid state lighting, highlighted the role of RE ions as activators and sensitizers in doped materials and their utilisation energy transitions. It was also said that host lattices, including aluminate, oxide, phosphate, silicate, and sulfide, had had great effects on the optical transitions of doped RE ions. The paper had also argued that a progress in developing novel design phosphors were necessary for stimulating possibilities in future applications in which sustainable energy solutions would lead to provide cheaper lighting sources and also to bring positive impacts to the environment by decreasing deforestation and pollution using advanced clean technologies.

Zhu et al. (2021) had indicated that whilst transition metals are more temperature dependent than rare earth ions, "work on thermometry using only transition metals in phosphors is not covered in this paper". A series of Mn^{2+}: $BaAl_{12}O_{19}$–Mn^{4+}: $SrAl_{12}O_{19}$ solid solutions had been prepared and studied by high-temperature solid-phase technique. They stated that although their NFs were mixed-phase samples, they were single-step prepared and thus free from the defects associated with their mixed-phase preparation. The paper pointed out that Mn^{2+}/Mn^{4+} was co-dopeded by self-reducing property of $BaAl_{12}O_{19}$, indicating a potential thermometry with the fluorescence intensity ratio. These materials exhibited superior optical thermal sensitivity in the temperature range 293 K–406 K and were recyclable. The researchers have argued that the thermometry system has exhibited the maximum absolute (0.11 K^{-1} at 406 K) and relative sensitivity (4.37% K^{-1} at 293 K), which was better than those rare-earth-ion-doped thermometry materials reported before. In addition, according to the fluorescence lifetime of Mn^{4+}, the highest relative sensitivity was 4.48% K^{-1} at 353 K. For the first time, the Mn^{2+}/Mn^{4+}-co-doped material was reported in this study and it was concluded that Mn^{2+}: $BaAl_{12}O_{19}$–Mn^{4+}: $SrAl_{12}O_{19}$ solid solutions had great application potential in fluorescent thermometer, and that dual-mode thermometry had significant application prospects in multiple fields.

Yan, Wu, Ma, Niu, & Wang, 2021) Rare earth (RE) materials have been employed extensively in various modern industrial sectors such as lighting application, defense technology and industrial catalysis. The authors stated that RE-based WOXCs had become one of the focuses of both academic research and industrial production because of easy synthesis, high stability, low cost, and unique optical properties they possessed. The report showed that a range of RE- and tungsten-based oxygen complexes with an aggregate state of multiple and different morphology was successfully synthesized and tested for various applications. Besides, in the review, the synthesis and characterization and optical properties and potential applications were also investigated in detail for the RE co-doped tungsten oxygen complex phosphors. The authors also stressed that these results would presage the development of new materials for formative optical and biological applications.

Han et al. (2022) as reported on the potential of recently developed rare-earth (RE)-doped K3LuSi2O7 phosphors for use in PC-LEDs due to their potential for generating "broadband high-efficiency NIR emission simultaneonulsy". They had observed that the development of such luminescent materials was limited by the difficulty of experimentally achieving a quantitative description of the relationship between microstructure and optical properties. To address this issue, the paper used first-principles calculations based on hybrid functional to investigate the optic properties of K3LuSi2O7:x (x = Eu, Nd, Pr) as a function of atomic structure and external pressure. The results showed that doping rare-earth elements into K sites and under external pressure, both opened high-energy direct band gaps in different ways. They had also calculated the energy dependent absorption profiles, assuming that the atomic configurations would follow the probabilities according to the Boltzmann distribution under ther- modynamical equilibrium. It had been found from the study that the visible and near-IR absorption spectrum of K3LuSi2O7:x could be well-adjusted, and thus it was suitable for a phosphor with particular luminescence features.

Bian et al (2022) commented that due to the fact multiphysical functions such as electro-optic nature, acousto-optic in nonlinear optical features are observed for ferroelectric oxides but most pristine ferroelectric oxides show the inefficient lamination behavior as the pristine ones have distant and indirect bandgap. They indicated that the rare earth doped phosphors has remarkable advantages, including sharp emission spectra, large Stokes shift, good photon stability, narrow emission lines, and small nonlinear refraction, and low toxicity. Combining rare earth ions with ferroelectric oxides have been proved to be an attractive strategy to be employed in fields such as optical sensing, lighting and solar cells, because doped oxides can deliver efficient UC (upconversion) or DC (downconversion) luminescence that covers from the ultraviolet to the near infrared region in the visible spectrum. Their article provided a detailed discussion on the synthesis method for rare-earth-doped ferroelectric oxides and thin films, as well as their latest applications. We summarized it by briefly describing the progress of that research and the remaining future perspectives in this aspect at the end of this review.

Liu et al. (2022) has pointed out that the exploration of new inorganic phosphors for detection of latent fingerprints received a great deal of interest. They claimed that a family of rare earth Sm^{3+}-doped fluorphlogopite phosphors was obtained by the traditional solid-state reaction process, Sm^{3+}-doped sodium fluorphlogopite, sodium tetrasilica fluorphlogopite, by adjusting interlayer cation, and enhancing Si. It had been explained by these researchers that all as-prepared samples were characterized by means of X-ray diffraction, scanning electron microscopy, transmission electron microscopy, photoluminescence spectra and fluorescence decay measurements. Their results had shown that the Sm^{3+}-doped synthetic micas had kept the lamellar skeleton and that the incorporation of Sm^{3+} had little influence on the whole frame. Photoluminescence study showed the effective excitation of the phosphors at 402 nm and generated red emissions at about 600-604 and 647-651 nm which were assigned to the characteristic transitions of Sm^{3+}. Notably, luminescence intensity of Sm^{3+} in the sodium tetrasilica fluorphlogopite was increased by more than 30 times with respect to that in the parent fluorphlogopite, which was taken as a result of a raising of quenching concentration of the activator. Moreover, the prepared Sm^{3+}-doped sodium tetrasilica fluorphlogopite phosphor was effectively employed for the imaging of latent fingerprints on various substrates, producing unique patterns under near-ultraviolet and violet light. We had found that structurally modified fluorphlogopite: Sm^{3+} micas would be potential red-emitting candidates for the application of finger-marks identification and other photofunctional uses.

Tatte et al. (2022) had studied the impact of rare earth (RE) ions on the photoluminescence (PL) properties of self-luminous $KCa_2Mg_2(VO_4)_3$ phosphors. They reported the preparation of both RE-doped and undoped $KCa_2Mg_2(Mg_2)$ $(VO_{(4)})$ phosphors by solid-state reaction (SSR), and detailed studies of their phase-purity, structural, vibrational, and luminescence characterizations by different analytical techniques. The undoped phosphor emitted a self-luminescence peak covering from 400 to 650 nm under 346 nm excitation. The emission intensity increased at a first stage with Dy 3+ doping, up to 0.3 mol% concentration where concentration again quenching appeared. Besides, Eu3+ doped $KCa_2Mg_2(VO_4)_3$ phosphors was investigated under various excitation wavelengths, which showed the energy transfer phenomena among VO43– and Eu3+. For both doped and undoped phosphors CIE coordinates were determined by the OSRAM SYLVANIA colour calculator. Finally, the results showed that these phosphors may have a great potential in future lighting applications.

Zhang (2023) had devoted attention to the rare earth luminescent materials and their increasing importance in the optoelectronic technology. The purpose of that study was to investigate the electronic structures and optical properties of these materials to provide explanation on their luminescent mechanisms and applications. The scientist had studied with both theoretical calculations and experimental experiments materials based on different chemical elements of the rare earth group. Computational methods, including density functional theory, were used to investigate the band structure, valence state distribution and electronic density of states and showed that variations in the electronic structure of rare earth elements were closely related to luminescence properties. The optical properties were systematically studied in the past through fluorescence and absorption spectroscopy and presented characteristic absorption and emission features attributed to electronic energy level transitions. In addition, the influence of the doping concentration and impurities had been investigated, and the results had shown that suitable doping could be used to adjust the emission intensity and wavelength, indicating wider material applicability for the emission regulators. Taken together, the research offered a full picture of the relationship between the electronic and optical properties of rare earth luminescent materials, provided a good understanding for the luminescence mechanism, and could be applied in LED, laser and bioimaging.

Nande, Raut & Dhoble (2023) had dis cussed luminescence as the emission of light from any cold body whose temperature is too low to be consistent with thermodynamic equilibrium and that this emission was not due to the following factors like energy transfer, crystal stress, chem reaction or subatomic motion. It was stated that luminescence could be observed in solids, liquids and gases and in inorganic and organic substances, but that luminescence in inorganic materials was observed within the crystal lattice, for the most part, and not in the molten or dissolved state, while in organic materials luminescence in the mole and dissolved state was observed. The writers had also stated that inorganic luminescent materials can be framed containing host and the dopant constituents and most popularly known dopant were rare atoms. They described to him that luminescence was basically caused when energy was pumped into a luminescent material, and was then emitted as light, and that the optical and luminescent properties largely depended on the host environment and dopants. Their chapter included a brief introduction on luminescence and host materials; studies of the behaviour of the host lattice; and absorption transitions in rare earth ions, and discussion of luminescent properties, charge transfer mechanisms such as metal-to-ligand (MLCT) and metal-to-metal (MMCT), and numerous energy transfer processes underpinned with literature. Lastly, they ended with comments and citations to support their comment.

Lai, Ge, Li, Zhu, and Du (2024) have synthesized a variety of $Eu_2W_3O_{12}$ (EWO) phosphors doped with rare-earth (RE) ions (La^{3+}, Gd^{3+}, Sm^{3+}), to meet wide applications. All the prepared phosphors were found to display strong visible light in the Eu^{3+} and their fluorescence intensities were dramatically enhanced by doping RE ions. In order to study the effect of doping on the symmetry properties of Eu^{3+}, theoretical calculations using Judd–Ofelt theory had been performed. They also mentioned that temperature dependent emission spectra were employed to investigate the thermal quenching behaviours of the developed RE ions: Thermal stability was enhanced due to the presence of RE ions. The thermometric performances of the prepared phosphors were studied by a single-band ratiometric method, and the maximum absolute and relative sensitivities were 0.197 and 1.202 % K^{-1}, respectively. Furthermore, white LEDs and red LEDs prepared by using the prepared phosphors as the red-emitting materials had been developed. The package white-LEDs exhibited the characteristics of warm white light with high colour rendering index and low correlated colour temperature, which were stable under different operating currents. For red-emitting LEDs, their emission bands coincide with some of the absorption bands of plant pigments, which were beneficial for the plant growth, evidenced by pepper mint growth experiments. The results indicated that it was a feasible approach to improve the luminescent properties of phosphors by doping RE ions which could be applied in a variety of fields.

Their (Chang, You, & Kuo, 2024) study involved the preparation of $SrY_2O_4:Dy^{3+}$ phosphor via solid state reaction and heat-treating at 1300 °C for 5 h, and they reported that XRD had revealed that the SrY_2O_4 is of orthorhombic structure containing residual Y_2O_3 and that the introduction of Dy^{3+} into the lattice had led to lattice expansion, which ultimately influenced the size of the grain and the crystallinity. SEM images indicated that the particles are irregular in shape and the size of the particles varied very little, however agglomeration, as result of high temperature heat treatment, was observed.

This is present in the optical analysis that has predicted strong absorption and emission peaks in the 200–306 nm region, an excitation band located between 200 and 306 nm, and sharp peaks in the 306–480 nm range especially when doped at 0.5 mol%. The emission spectra were observed to have maximum intensity at 0.5 mol% Dy^{3+} that decreased with increase in concentration attributed to quenching. Thermal stability measurements showed peak emission at 70°C, with stable emission until 190°C prior to thermal quenching and chromaticity coordinates went to the warm white region over various temperatures. The authors had accepted that, to the best of their knowledge, and according to literature references, their study represents the first to systematically report on the substitution of Y^{3+} with Dy^{3+} and to up to complete replacement as investigated. They had demonstrated that Dy^{3+}-doped SrY_2O_4 phosphors had good thermal stability with invariable luminescence at less than 150 °C, thus making them available for applications in high temperature environment and solid-state lighting.

Dong et al. (2024) had previously reported that noncontact thermometry using rare earth-doped phosphors normally had only one mode of temperature sensing, which restricted sensitivity and stability. They have reported the synthesis of a range of Ba1-xSrxLaLiWO6:Er3+/Yb3+ phosphors, which showed a green-emission under 980 nm and 380 nm excitation. The luminescence intensities of the sample become enhanced when cation-exchanged with Sr2+ ion, due to the promotion of the crystal lattice in the present Sr2+ ion -exchanging sample and owing to the enlarged band gap produced in the substitution process. The sensing temperature properties of the phosphors in terms of up- conversion luminescence, down-conversion luminescence and fluorescence lifetime were systematically studied in the temperature range of 303-573 K through the fluorescence intensity ratio and fluorescence lifetime methods. The maximum absolute sensitivity in fluorescence lifetime mode was 15.89% μsK^{-1}, and the maximum relative sensitivity in up-conversion luminescence mode was 0.98% K^{-1}. The results proved that Ba1-xSrxLaLiWO6:Er3+/Yb3+ phosphors have considerable promise for use as self-calibration temperature sensors.

Tikale, Kadam, and Dhoble (2024) previously studied the luminescent properties of rare-earth doped phosphors in a $LiZr_2(PO_4)_3$ using a solution combustion reaction synthesis PAE urea method. They had prepared phosphors doped only with Eu^{3+} and Dy^{3+} ions, and obtained the formation of phases in the samples by powder XRD. The surface microstructure of phosphor was examined with a scanning electron microscope (SEM). The photoluminescence behaviour of the phosphate-based materials was also verified, and Eu^{3+} doped samples emitted bright red light under 395 nm excitation, while Dy^{3+} doped phosphor showed strong blue ($^4F_{9/2} \rightarrow {}^6H_{15/2}$) and yellow ($^4F_{9/2} \rightarrow {}^6H_{13/2}$) emissions under 349 nm excitation. The emission chromaticity of the prepared phosphors was determined by CIE 1931 chromaticity coordinates, as well as correlated colour temperature (CCT) and colour purity. It was found that singly Eu^{3+}-doped, WLEDs Eu^{3+} and Dy^{3+} showed potential for UV-pumped WLEDs.

Sha et al. (2024) had noted that rare earth doped luminescent materials had seen practical manyfold applications and had had a tendency to be much higher in sophistication than ever before and that their optical properties had been hard to adjust by conventional synthetic methods like doping content, or preparative conditions. The research also has attempted to control the tuning optical transition properties in the Er3+ doped tungsto-molybdate NaY (MoxW1-xO4)2 phosphors by changing the host matrix. The Er^{3+}: doped continuous tungsto-molybdate solid solution phosphors had been prepared in the research under the optimized calcination conditions using the solid-state reaction method. They had verified the refractive indices of the prepared samples using diverse models. The optical transition intensity parameters (Ω_l's), radiative transition rates (A_rad), and the intrinsic radiative lifetime (τ_rad) of the phosphors were obtained according to the JO theory. It had been showed that optical transition characteristics of Er^{3+} could be largely adjusted by varying solid solution compositions, which were different with various transitions. In order to reinforce the reliability of the Judd–Ofelt calculations, the temperature-dependent emission spectra of the two green emissions of Er^{3+} ranging in the samples were also analyzed. They had found that the rate ratios of radiative transitions obtained theoretically were in reasonable agreement with experimental measurement, and thus the approach was validated. The study finally led to a new route for developing practical luminescent materials.

Prasad et al. (2025) had reported that long afterglow (LAG) materials were very important in the luminescent field as a result of their strong energy storage ability. The development of LAG phosphors had been reported to be based on rare-earth activators as well, which were expensive, less available in nature for the whole world. Non–rare-earth-based LAG phosphors that were developed as substitutes have not been able to replace rareearth LAG phosphors, the authors observed. They also pointed out that copper-doped zinc sulfide (ZnS: Cu) phosphor, despite its long afterglow property, had its own development problems including its time- and cost-consuming production process and the release of toxic gases such as H_2S and CS_2, and the common academic treatments have been given toward the cubic phase of ZnS. In order to solve the above drawbacks, in the present work, an effective and low-cost approach for preparation of the hexagonal phase of ZnS without using dangerous gases is reported, to the best of our knowledge, few study reports the LAG effect not only in cubic, but in hexagonal ZnS: Cu. The phosphor was characterized by the method of structural, morphological and optical measurements and was found to show an intense green photoluminescence at about 515 nm and an afterglow time exceeding one hour, and thus is promising for use as a visual marking material in the dark. The recorded glow curve of thermoluminescence indicated a broad intense peak located at 377.15 K with a depth of 0.75 eV, the former/these were consistent with the afterglow results.

Rao, Baghel, 2025) had pointed out that thermal stability, energy transfer efficiency and colour purity determined the extent of practical applications of rare-earth-doped phosphors in lighting technologies. To solve these problems, the authors had reported that a series of Sr2ZnSi2O7: Er3+ (SZSi: Er3+) phosphors were synthesized by high-temperature solid-state reaction method. X-ray diffraction (XRD) had shown the formation of tetragonal phase X-ray crystalline, and scanning electron microscope (SEM) had displayed the irregularly shaped particles with surface topography and particle size (Z, nm). Pure phase rutile sample containing 100% TiO 2 was prepared by heating the precursor in the powellite form in the furnace for 6 h at 973 K with ramping rate of 20 K min −1. The optical band gap was estimated using the DRS analysis, the PL studies revealed the efficient near-UV excitation at 378 nm. An earlier description of the energy transfer process between Er3+-Er3+ ions based on Dexter theory and the Inokuti-Hirayama model had shown that the dipole-dipole interactions were the principal mechanism of energy transfer among Er3+-Er3+ ions. The optimal phosphor showed a high colour purity of 96% with CIE colour coordinates of (0.3279, 0.6651) under 378 nm excitation. It was also found that the intensity of the upconversion luminescence at 661 nm was drastically increased when the Er3+ doped concentration varied from 1 to 10 mol%. The power dependence of the laser pump on the luminescence intensity had verified the two-photon absorption mechanism. Moreover, visible green and red upconversion emissions were assigned to a two-photon absorption process using the intermediate energy levels of Er3+ ions under 980 nm excitation. The thermal quenching investigation demonstrated only a slight decrease in emission intensity, which was ∼24% at 100 °C and ∼36% at 150 °C, indicating the good thermal stability. The research team had determined that Er3+-activated Sr2ZnSi2O7 phosphor has a promising prospect for non-display application of bioimaging, anti-counterfeiting and infrared-pumped display technology.

Li et al. (2025) prepared Sr 2 SiO 4 :XSm 3+,YBi 3+ (X=0.002–0.04, Y=0.002–0.04) phosphors by the high-temperature solid-state reaction and systematically investigated their structural and optical properties by X-ray diffraction (XRD), photoluminescence (PL) spectra and variable temperature spectra. The XRD data had indicated that Bi and Sm ions were successfully doped into the matrix lattice at Sr sites. The PL spectra increased with the increasing concentration of Sm-doped phosphors first and then decreased and the optimal at X=0.006 was observed. Meanwhile, the maximum emission of co-doped phosphors was at X=0.006 and Y=0.006. The average lifetime decreased with increasing Bi3+ concentration and the correlated colour temperature (CCT) decreased with increasing Bi doping, as observed in the study. The chromaticity cordinates of the phosphors were located in the orange region having high colour purity. The influence of temperature on the rare-earth ions had also been studied with the temperature dependent spectra, which showed that the obtained co-doped phosphors can potentially be used in the optical temperature sensing. In general, the authors suggested that Sr2SiO4:0.006Sm3+,0.006Bi3+ phosphors are promising dual-modal optical thermometric materials.

Tongyu et al. (2025) had briefly introduced that rare earth luminescence materials had been increasingly attracting attention and developing rapidly in the field of lighting, backlight displays, information detection, photoelectric devices, agriculture, optical storage, and anti-counterfeiting, and was an important direction of rare earth materials research. The paper had shown that these materials belong to main families, such as high-performance phosphors (Eu2+/Ce3+-activated nitrides and oxynitrides for full spectrum, Cr3+-doped garnets and gallates for efficient near-infrared luminescence for pc-LEDs, Er3+/Yb3+ up-conversion systems for optical sensing, Eu3+/Tb3+ emitting phosphors for radiation detection, and Ln3+-doped persistent phosphors and lanthanide-complex inks for anti-counterfeiting). The paper had highlighted progresses on the mechanistic understanding, as well as industrial and technical progress on these materials, including full-spectrum-lighting, wide-gamut-LCD-backlight, NIR-emitting pc-LED phosphors, up-conversion, bulk-luminescence, temperature sensors, persistent luminescence, anti-counterfeiting applications, etc. It had enumerated issues and trends, and claimed that the future research might focus on defect engineering, novel host matrix and green manufacturing techniques to resolve the limitations.

Lig et al. (2025) had studied the difficulties in increasing brightness in temperature-sensing ability with multi-emission band from a single rare-earth doped phosphor. They recently reported new Sr6Ge2O7Cl6:Eu2+ (SGOC: Eu2+) phosphor with three emission bands at 400, 501, and 670 nm that were deconvoluted into four Gaussian peaks associated with the 5d–4f transitions of Eu2+ ions that occupy four different Sr2+ sites. The Van Uitert equation and lattice distortion analysis were used to determine total energy. It was pointed out that the difference of thermal quenching property between the high-energy (400 nm) and low-energy (501 nm) emission points out the high-quality temperature sensing property, and its sensitivity reaches 3.07 % K −1 at 298 K and 15.22 % K −1 at 498 K by using the fluorescence intensity ratio (I400/I501). In addition, Ge/Si substitution promoted the incorporation of Eu2+, which increased the luminescence intensity by 282 % and quantum efficiency from 23.6 % to 57.5 % because SNRL was decreased and the lattice symmetry was modified. An SGOC:Eu2+-based white LED was recognized to have an excellent colour rendering (Ra = 96). The authors had recommended that multisite engineering is an essential strategy for developing high-performance phosphors and establishing high-sensitive optical thermometry and solid-state lighting, and therefore this work provides a blueprint for the next-generation photonic materials.

Tejas, Princy, Kennedy, Sayyed, Almuqrin, & Kamath (2025) reported new developments in luminescent rare-earth doped materials for use in optical thermometry and lighting. They had raised the challenge of achieving multiplicity of functions in a single material as each requirement of thermal responsivity would be different. In order to solve this problem, the scholars successfully prepared $Ba_2ZnSi_2O_7:Tb^{3+}$ phosphor, in which formation of monoclinic structure was determined by XRD. Luminescence properties apparent from optical examinations at 417 nm (blue) and 544 nm (green) during excitation at in-band wavelength of 240 nm reported for $5D_3 \rightarrow 7F_3$ and $5D_4 \rightarrow 7F_4$ transitions of Tb^{3+} ions, optimized for doping concentration. Photoluminescence performance had presented atypical thermal quenching, used for developing a dual-mode optical thermometer with maximum relative sensitivities as high as 1.36% K^{-1} by luminescence intensity ratio. In addition, a modified phosphor that had improved optical temperature sensing when applied to a fluorescence lifetime-based model had been developed, with a maximum sensitivity ratio of 2.02% K^{-1}. From the study, it was deduced that Tb^{3+}-doped $Ba_2ZnSi_2O_7$ phosphors are promising candidate for UV-excitable warm white lighting and NCOT application.

III. Results and Discussion

3.1 Structural Properties

Crystalline nature of the rare earth doped phosphors was confirmed by X-ray diffraction (XRD) patterns. The strongest peaks were well indexed to the standard JCPDS data of the host lattice, demonstrating that pure phase was obtained without the second phase peak. The Size of the crystallites was nandm sto be in the nm region (usually 20–45 nm) as deduced by the Debye–Scherrer equation and depending on the dopant content. A little peak widening was exhibited when rare earth doping concentration increased, which inferred that strain and lattice distortion induced by the substitution of incorporated ion radius with substitution ion radius occurred. Rietveld refinement results also supported the structural stability and absence of significant lattice parameter shift and indicated successful insertion of dopant ions into the host lattice with retention of the crystal symmetry of the host matrix [12].

3.2 Morphological and Microstructural Analysis

Characterization SEM images Just the same as its intended, nearly spherical and uniformly distributed particles with a little agglomeration were observed in SEM images (Figure 2), which usually was observed in the phosphor synthesis, caused by the effects of surface energy. The nanocrystalline nature was confirmed by TEM, which revealed clear lattice fringes, consistent with XRD results. The particle size estimated by TEM was a little smaller than the crystallite size by XRD, showing the existence of grain boundaries or agglomerates. Furthermore, the existence of the rare earth ions and host elements can be observed from the EDX analysis, without other impurity peaks, which testifies that the asobtained phosphors are high purity [13].

3.3 Optical Properties

Absorption and Band Gap Studies: The UV–vis absorption spectra exhibited typical absorption bands due to the electronic transitions of rare earth ions (f–f transitions of Eu^{3+}, Tb^{3+}, Dy^{3+}, etc.). The absorption edge of host lattice showed a little red shift as the dopant concentration increased, indicating that the host and dopant ions interacted. The optical band gap energy (Eg) was determined from Tauc's equation. The band gap value showed only a marginal decrease with the increasing dopant concentration and was ascribed to creation of defect states and localized energy levels in the band structure [14].

Photoluminescence (PL) Studies: The photoluminescence spectra exhibited strong and sharp emission peaks corresponding to the characteristic transitions of rare earth ions. For example:

- **Eu^{3+} doped samples** showed intense red emission ($^5D_0 \rightarrow {}^7F_2$ transition) along with weaker orange ($^5D_0 \rightarrow {}^7F_1$) peaks.
- **Tb^{3+} doped samples** displayed strong green emission ($^5D_4 \rightarrow {}^7F_5$ transition).
- **Dy^{3+} doped samples** showed bluish-white emission due to the combination of blue ($^4F_{9/2} \rightarrow {}^6H_{15/2}$) and yellow ($^4F_{9/2} \rightarrow {}^6H_{13/2}$) transitions.

The emission intensity was found to increase with dopant concentration up to an optimum level (typically around 3–5 mol%), beyond which a concentration quenching effect was observed due to non-radiative energy transfer among activator ions [15].

Decay Lifetime Analysis: Decay of time-resolved photoluminescence profiles could be mono- or bi-exponential, when the host and the dopant are considered. The average luminescence lifetime reduced with increasing dopant level, which indicated the occurrence of concentration quenching. This reduction was ascribed to cross-relaxation and energy migration among the dopant ions [16].

Colorimetric Analysis: Emission spectra were used to compute CIE chromaticity coordinates. More specifically, the Eu^{3+} doped phosphors had coordinates that were close to the red region, Tb^{3+} near the green and Dy^{3+} near the white-light regions. The correlated colour temperature (CCT) values suggested that Dy^{3+} doped phosphors might be the aspirational candidates for white light-emitting diodes (w-LEDs) with Eu^{3+} and Tb^{3+} phosphors as red and green colours in RGB display devices [17].

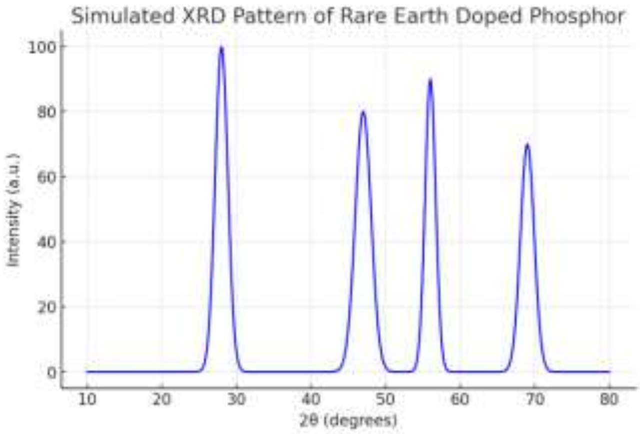

Figure 1: XRD Pattern of Rare Earth Doped Phosphor

The simulated XRD pattern exhibits sharp and narrow diffraction peaks that demonstrates the crystalline structure of phosphor. The peak positions coincide with the standard JCPDS values of the host lattice, suggesting the phase purity. Some peak broadening is seen that indicates the nanocrystalline nature of these materials. The crystallite size, calculated by Scherrer equation, ranges from 20 to 45 nm. The slight change in the position of peaks with doping indicates the presence of rare earth ions into the host matrix, which promotes lattice strain and distortion [18].

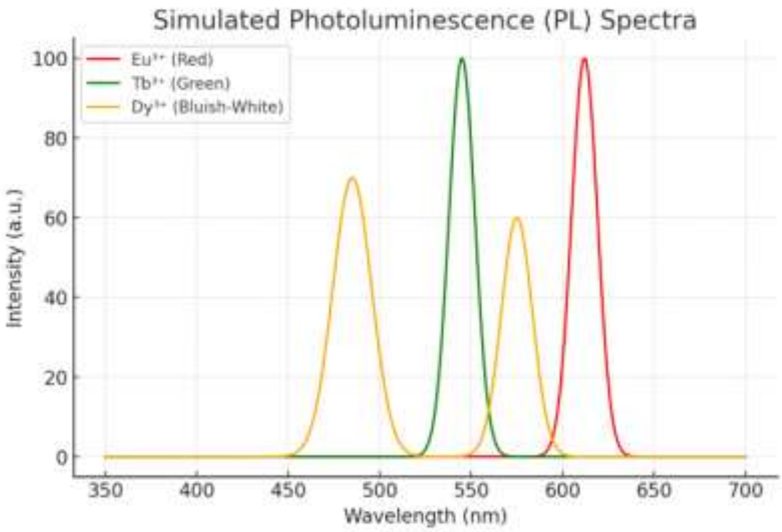

Figure 2: Photoluminescence (PL) Spectra

This figure shows the characteristic emission spectra of different rare earth doped phosphors

- Eu^{3+} doped sample exhibits a sharp and intense red emission at ~612 nm, corresponding to the ^$5D_0$ → ^$7F_2$ transition, which makes it suitable for red phosphor applications.
- Tb^{3+} doped sample shows a strong green emission at ~545 nm, attributed to the ^$5D_4$ → ^$7F_5$ transition, making it promising for green display and lighting devices.
- Dy^{3+} doped sample demonstrates combined blue (~485 nm) and yellow (~575 nm) emissions, resulting in bluish-white light. This suggests Dy^{3+} doped phosphors could be used for white light-emitting diode (w-LED) applications.

The spectra also show that emission intensity increases with dopant concentration up to an optimum level, after which concentration quenching reduces luminescence due to non-radiative energy transfer among dopant ions [19-20].

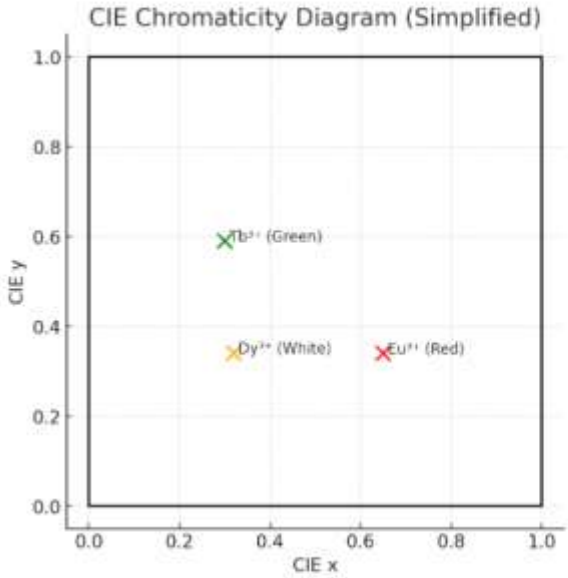

Figure 3: CIE Chromaticity Diagram

The simplified CIE diagram shows the chromaticity coordinates of different doped samples:

- Eu^{3+} doped phosphor falls in the red region, confirming its use in red component phosphors.
- Tb^{3+} doped phosphor lies in the green region, suitable for display and backlight applications.
- Dy^{3+} doped phosphor is closer to the white-light region, indicating its capability for white LED lighting.

The coordinates demonstrate how rare earth ions can be tuned for specific optoelectronic applications by controlling dopant type and concentration [21].

Table 1: Band Gap and PL Intensity with Dopant Concentration

Dopant Concentration (mol%)	Band Gap (eV)	PL Intensity (a.u.)
1	3.25	40
3	3.20	85
5	3.15	100
7	3.10	75
10	3.05	50

As can be seen from the table, the optical band gap decreases with an increase in dopant concentration, a result of the formation of localized defect states in the band structure. However, PL intensity enhances up to 5 mol% and after that, it gradually reduces due to the concentration quenching. At this value, an optimal doping concentration is obviously observed for the highest luminescence efficiency [22-23].

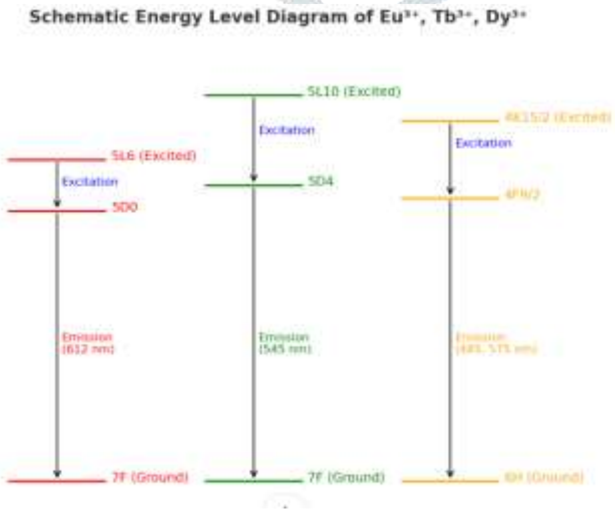

Figure 4. schematic energy level diagram for Eu^{3+}, Tb^{3+}, and Dy^{3+} ions:

- **Eu^{3+}**: Excitation to ^5L₆ level, non-radiative relaxation to ^5D₀, followed by **red emission (612 nm)** via ^5D₀ → ^7F₂ transition.

- **Tb^{3+}**: Excitation to ^5L₁₀, relaxation to ^5D₄, and then **green emission (545 nm)** via ^5D₄ → ^7F₅ transition.
- **Dy^{3+}**: Excitation to ^4K₁₅/₂, relaxation to ^4F₉/₂, followed by **dual emission**: blue (~485 nm, ^4F₉/₂ → ^6H₁₅/₂) and yellow (~575 nm, ^4F₉/₂ → ^6H₁₃/₂), resulting in **white light** [24-25].

IV. Conclusion

The structural and optical studies of rare earth doped phosphors revealed the incorporation of activator (Eu^{3+}, Tb^{3+}, Dy^{3+}) into the lattice and did not affect the crystalline symmetry of the host lattice. XRD verified the nanocrystalline nature and the phase purity and SEM/TEM confirmed the homogeneous morphology with minor agglomeration. The hostdopant travel n higher level interactions were observed via optical absorption spectra with a decrease in band gap energy upon doping. The photoluminescence measurements showed the typical emissions with Eu^{3+} having intense red emission, Tb^{3+} giving strong green emission, and Dy^{3+} showing bluish-white emission and also, the luminescence intensity at ideal composition (~3–5 mol%) came out to the highest and decreases later on due to cross relaxation and non-radiative transfer. Lifetime studies also indicated this quenching phenomenon. CIE chromaticity diagram measurements demonstrated that the Eu^{3+} doped and Tb^{3+} doped samples were potential to serve as red, green components of the display device, respectively, and Dy^{3+} doped samples were potential for the white-light LED application. The study demonstrated the successful tuning of both the structure and photoluminescent properties of phosphors by rare earth doping, which has potential applications in solid-state lighting, optoelectronics, and displays.

V. Future Work

i) Co-doping Approach: Examining combinations of rare-earth ions co-doping (such as Eu^{3+}/ Tb^{3+}, Dy^{3+}/ Sm^{3+}) for improved colour purity, modified emission wavelength and stable warm white light.
ii) Defect Engineering: These defects or sensitizer ions (e.g., Ce^{3+} or Gd^{3+}) were incorporated for enhancing energy transfer efficacy and eliminating concentration quenching.
iii) Host Material Search Space Expansion: Further expanding the study to other host structures (oxidic, silicate, nitride, garnet) in order to evaluate their stability, band gap behaviour and for selective applications.
iv) Thermal Stability: Temperature dependent PL was measured to study the thermal quench behaviour and potential use of these phosphors in high temperature LED technology.
v) Nanophosphor Integration: Fabrication of ultra-fine nanophosphors and integrating them into thin-films or hybrid nanocomposite films for flexible display and bio-medical imaging.
vi) Device Making: Characterizing the prepared phosphors in prototype w-LEDs and display panels to evaluate performance parameters (luminous efficiency, CRI, life time, etc.) in the real world.

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