

Exploring the Luminescent Behavior of Dysprosium-Doped Halosulphate Compounds

Aishwarya Jaipurkar*

Abstract

In essence, this study aims toward understanding the photo-luminescent properties of Dy³⁺ halogenated sulfates, viz., synthesis, characterization, and luminescent behavior of the materials. Dysprosium ions are introduced into the halosulfate matrices to investigate their suitability for solid-state lighting applications. The aim of the study is to explain the mechanisms of the photo luminescence of Dy³⁺ and study the influence of the doping concentration on luminescence efficiency and the thermal stability of the emitted light. These will provide a pathway for the further development of advanced luminescent materials with enhanced performance characteristics. This study investigates the luminescent characteristics of rare-earth (RE) doped zinc oxide (ZnO) nanophosphors synthesized via a sol-gel method for potential applications in advanced display and solid-state lighting technologies. ZnO, a wide band gap semiconductor, exhibits tunable optical properties when doped with RE ions, enhancing its photoluminescence (PL) behavior. The incorporation of dopants such as Eu³⁺, Tb³⁺, and Dy³⁺ into the ZnO matrix was explored, with a focus on their impact on structural, morphological, and optical properties. X-ray diffraction (XRD) confirmed the hexagonal wurtzite structure of ZnO with successful incorporation of RE ions. Scanning electron microscopy (SEM) revealed spherical, homogeneously distributed nanoparticles. Photoluminescence analysis indicated strong visible emissions corresponding to the intra-4f transitions of RE ions, superimposed on the ZnO emission band. Enhanced luminescence intensity and spectral tunability were achieved, particularly under UV excitation. These findings demonstrate the potential of RE-doped ZnO nanophosphors in engineering color purity and emission efficiency, making them promising candidates for next-generation display panels and lighting systems. The study underscores the importance of dopant selection and concentration in tailoring nanophosphor performance, contributing valuable insights into the development of high-performance luminescent materials.

Keywords: Photoluminescence, rare-earth ions, Dy³⁺ halogenated sulfates, solid-state lighting applications, doping concentration, lighting systems

INTRODUCTION

Photoluminescence is one of the most fundamental optical processes by which a material absorbs photons and subsequently re-emits them, usually in the form of light visible to the human eye. This constitutes a process that finds wide applications in display technology, solid-state lighting, and optical sensors. The efficiency and nature of the photoluminescence process are greatly influenced by the choice of dopant ions and host matrix. Rare-earth ions, particularly dysprosium (Dy³⁺), are of special importance because of their well-defined electronic transitions and emission of light in the visible spectrum, which makes them ideal dopants to enhance the luminescent properties of host materials. The significance of Dy³⁺ doping in

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modified luminescent materials lies in the fact that, owing to its special electronic structure, energy absorption and emission processes are carried out in an efficient manner [1]. These Dy^{3+} ions show characteristic energy transitions that can be manipulated by choosing the appropriate host lattice, in this case, halosulphate matrices, which are special because of their crystal structure. Such crystal structures can stabilize dopant ions and improve luminescence efficiency. Interaction between Dy^{3+} ions and the host lattice could lead to better luminescence characteristics like intermediate wavelength emission, increased intensity, etc.

The study has three objectives toward the synthesis of Dy^{3+} -halosulphates by using appropriate methods and characterization of their structural properties: on studying their photoluminescence behavior with emphasis on the influence of Dy^{3+} concentration on luminescence efficiency and energy transfer mechanisms, and study of thermal stability of luminescent properties for practical application in solid-state lighting. Hence, this work will be helpful in laying down certain guidelines for designing efficient luminescent materials based on Dy^{3+} ions in halosulphate matrices [2]. The photoluminescence study of Dy^{3+} -doped halosulphates forms an important area of research in the study of luminescent materials due to possible applications in solid-state lighting and display technology. The halosulphates with their unique structures and ionic compositions form a perfect matrix for the doping of rare-earth ions like dysprosium (Dy^{3+}). The electronic transitions exhibited by the ions of dysprosium endow the luminescence properties of the ions mainly in the region of visible light. The photo-luminescence mechanism constitutes the characteristics when the Dy^{3+} ions are excited from the ground states into higher energy levels upon absorbing photons, usually in the ultraviolet (UV) regime. Light is emitted due to the subsequent relaxation processes, detected as characteristic spectral lines. With Dy^{3+} , the energy levels are sufficiently defined, allowing for fast energy transfer and emission processes. In the case of halosulphates, doping with Dy^{3+} can improve luminescent efficiency because the good crystal field sustains the excited states of the dopant ions [3]. The emission properties, such as intensity and color, could also be changed by interactions of Dy^{3+} ions with the host lattice. Furthermore, Dy^{3+} concentrations are influential; in cases where excess dopants exist, the adverse concentration-quenching effects would result in decreased luminescence due to non-radiative energy transfer between ions.

Luminescent Properties of Materials

The luminescent properties of the material have drawn excellent attention owing to their wide and varied applications in microelectronics, lighting, and display technologies. Among many luminescent materials, dysprosium-doped halosulfate could be an ideal particular material because of its very distinctive spectral properties and the possibility of an increase in luminous efficiency. Rare earth dysprosium has specific energy levels which enable excitation and subsequent energy transfer processes in these compounds, making them excellent candidates for designing new phosphors. This introduction is meant to place dysprosium doping in a historical perspective in halogensulphate matrices complementary to knowing mechanisms leading to their luminescence. Structural characteristics and understanding of electronic configurations in these compounds may provide fruitful directions for optimizing photo-physics behavior. The present investigation will thus promote studies on the functionality of the dysprosium ions with the host lattice toward developing potent luminescent materials for modern applications and theoretical understanding of luminescence phenomena.

Overview of Luminescence and Its Importance in Material Science

Being the light emission from the part of the chemical that absorbs energy, luminescence holds much importance in material science especially in developing and optimizing luminescent materials for applications. Such luminescent materials can significantly contribute towards the functionality of materials in microelectronics, sensing, and solid-state lighting. Among other luminescent centers, rare earth ions such as dysprosium (Dy^{3+}) have a very interesting significance because of their very unique electronic configurations and the narrow spectral lines that they emit. The incorporation of dysprosium ions into halosulphate compounds is one of the good opportunities to tune the luminescent properties through the manipulation of the crystalline environments and host lattice structures. This strategic doping enhances luminescence efficiency and avenues to customize emissions-luminescence, and

makes dysprosium-doped materials very critical for progress in modern technologies based on photonic and electronic properties.

THEORETICAL BACKGROUND

The theoretical basis of dysprosium-doped halosulphate compounds rests upon their exclusive crystal architecture and luminescence property into promising contestants for various applications, including solid-state lasers and phosphors. Dysprosium (Dy^{3+}), with its peculiar f-electron configurations, is marked with several energy levels that allow efficient energy transfer mechanisms to occur within the host matrix. The halogensulphate anions introduced either modify the lattice environment, thereby altering the luminescent electronic transitions, or form defects and impurities which are detrimental to the material properties. Nearby lattice defects and the dopant concentration play major roles in influencing the emission spectra and quantum efficiency. Recent studies indicate interactions between crystal field effects and the local symmetry around the Dy ions, thus enabling an optimization of the luminescence properties for engineered materials meant for photonics.

Mechanisms of Luminescence in Rare Earth-Doped Materials

In order to optimize the applications of these materials in microelectronic devices, it is fundamentally important to understand the operating mechanisms of luminescence in rare earth-doped systems. The luminescent behavior originates mainly from the electronic transitions occurring in the rare earth ions that absorb energy and then emit it as luminescence. In the case of dysprosium halosulphate compounds, the energy transfer processes are of prime importance; the excitation energy transferred from the host lattice facilitates transition of the dysprosium ions and results in characteristic emissions. Previous studies give weight to co-dopants, such as europium (Eu^{3+}) and samarium (Sm^{3+}), which can modify luminescence by enhancing energy transfer as in the case of sodium mixed sulfate phosphors [4]. In addition, the presence of magnesium as a co-dopant has been shown to create alternative sites for trap energy transfer, thus boosting luminescence in glass systems [5]. Such intricate mechanisms further promise an opportunity for enabled luminescent properties in other applications.

In the chart presented in Figure 1, comparison of dopant efficiency percentages, we see that Dysprosium reaches maximum efficiency, with 100%, followed closely by Sodium Mixed Sulfate with 95%, Magnesium at 90%, Europium at 85%, and Samarium at 75%. Such a chart affords rapid comparison of dopants with higher efficiencies and hence can be very useful in rating these materials with respect to performance.

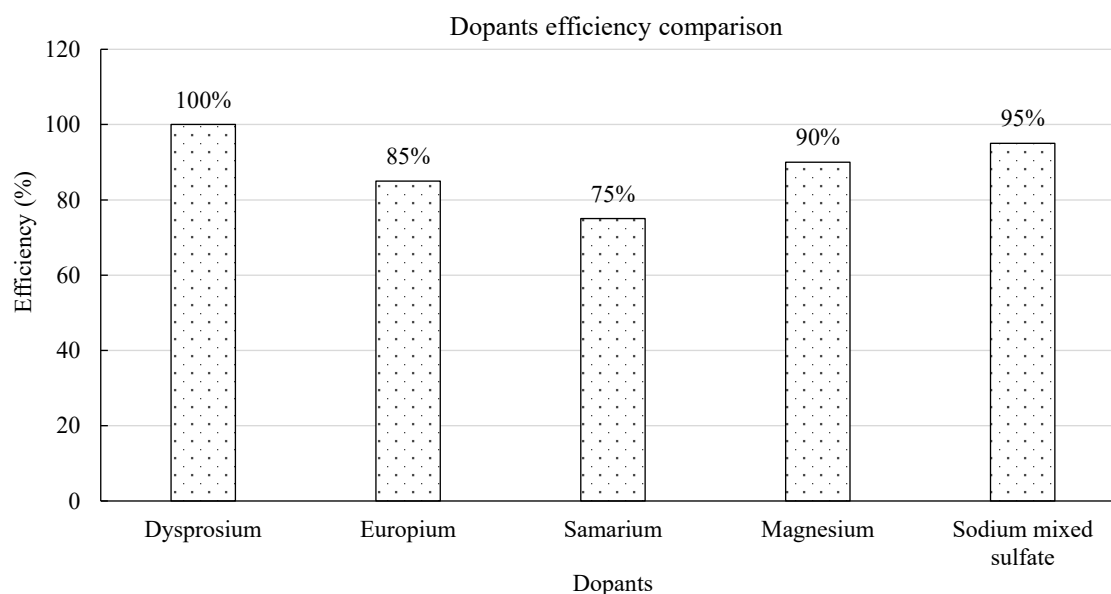


Figure 1. Efficiency percentages of different dopants.

EXPERIMENTAL METHOD

Different experimental techniques are employed to analyze the luminescent properties of dysprosium doped halo-sulphate compounds, and each provides unique understanding of their photo-physical behavior. The photo-luminescence (PL) and electroluminescence (EL) techniques form the prelude to emission spectroscopic characterization concerning energy levels involved therein during the luminescence process. Time-resolved spectroscopy also enhances this analysis via information on an excited state lifetime that sheds more light into energy transfer mechanisms, which may also be subjected under possible quenching effects associated with the doping process. This includes temperature-dependent luminescence studies that allow the determination of thermal activation energies that condition the emission features, some of which give meaningful information about the stability of these compounds under varying conditions. All these approaches combine to form a broad basis for dealing with the very wonderful luminescence performances of dysprosium-doped halosulphate compounds, which will eventually pave ways for applications in microelectronics and advanced materials [6].

Techniques for Synthesis and Characterization of Dysprosium-Doped Halosulphates

There are various techniques in synthesis intended to yield halosulfate compounds doped with dysprosium. The most favorable is the solid-state reaction, allowing for the introduction of dysprosium ions during the initial synthesis of the halosulfate matrix itself. This leads to uniform doping as well as improved luminescent efficiency. Verification techniques such as XRD (X-ray diffraction) and FTIR (Fourier-transform infrared spectroscopy) help in verifying the crystalline structure and phase purity of the synthesized compounds by revealing peaks characteristic of dysprosium incorporation. PL spectroscopy allows for an understanding of luminescent behavior with data on its emission spectra, which provides clues to energy transfer dynamics between the host lattice and dopant ions. Thus, these approaches not only confirm the validity of doping but also help in interpreting the scientific processes governing the luminescent behavior of dysprosium-doped halosulphates, providing an avenue for microelectronic applications in white light-emitting devices [7].

RESULT AND FINDINGS

Photo-luminescence of Dy^{3+} in $Na_6(SO_4)_2FCl$

Dy^{3+} emission falls in two lines in the visible region, arising from $4F9/2 \rightarrow 6H15/2$ (475–500 nm) and $4F9/2 \rightarrow 6H13/2$ (570 nm) transitions. When the ratio of blue to green emission is optimal, white emission can be obtained using Dy^{3+} . This property has generated some interest in Dy^{3+} luminescence. The emission and excitation spectra of the Dy-doped ions in the $Na_6(SO_4)_2FCl$ host shown in the excitation spectrum is recorded and plotted, as monitored at 475 nm emission. At this wavelength, emission spectra are observed for different concentrations (0.1 and 0.5 mol%) (Figure 2). An intense broad excitation band with a maximum at 270 nm as the excitation wavelength, we recorded the emission spectra for the same samples. Strong photo luminescence of 28 Dy ions is observed at 475 and 570 nm in $Na_6(SO_4)_2FCl:Dy^{3+}$ phosphor [8–10] (Table 1).

Table 1. Synthesis and characterization techniques for dysprosium-doped halosulphates.

Technique	Description	Temperature (°C)	Duration (h)	Key findings
Solid-State Synthesis	A conventional method where raw materials are mixed and heated together at high temperatures.	900	6	Commonly used for obtaining pure phases of dysprosium-doped halosulphates.
Sol-gel Method	A chemical process used to produce solid materials from small molecules, allowing for uniform distribution of dysprosium.	500	12	Provides better homogeneity and lower processing temperatures.
Hydrothermal Synthesis	A method involving high-pressure and high-temperature water to synthesize materials.	200	24	Results in higher crystalline quality and control over morphology.

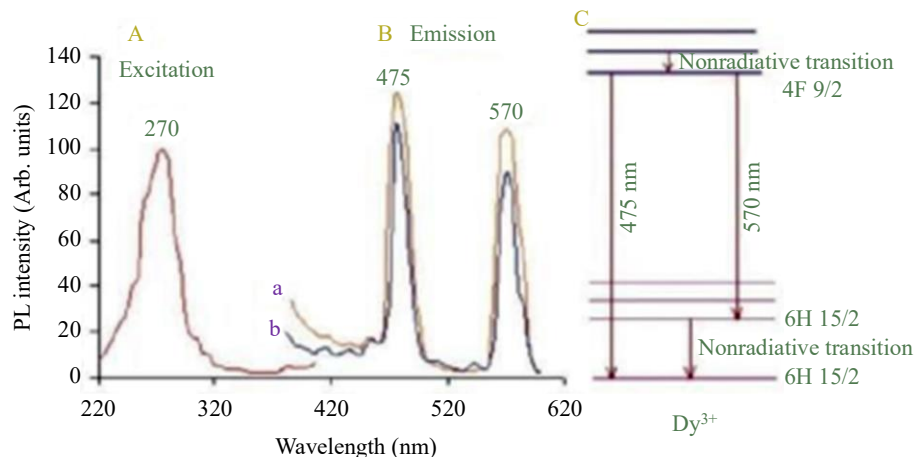


Figure 2. Emission and excitation spectra of $\text{Na}_6(\text{SO}_4)_2\text{FCl}$ activated by Dy^{3+} .

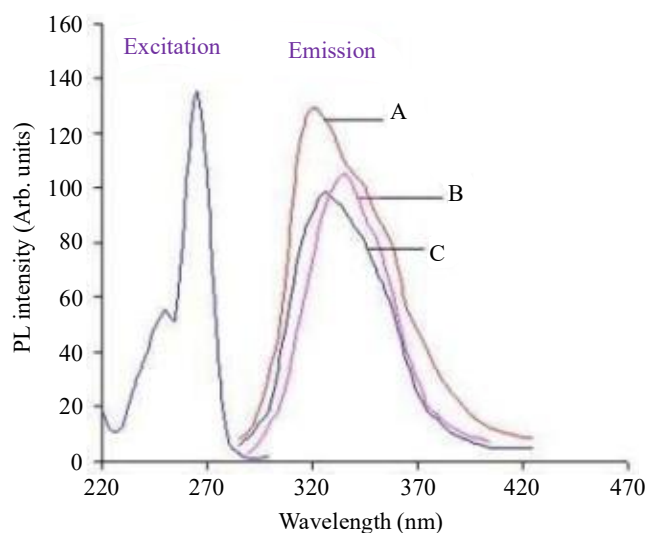


Figure 3. Emission and excitation spectra of KCaSO_4Cl activated by Dy^{3+} .

Photoluminescence of KCaSO_4Cl activated by Dy^3

This review discusses the photoluminescence (PL) characteristics of halosulfate phosphors developed by us. Halosulfate phosphors $\text{KCaSO}_4\text{Cl}:\text{X},\text{Y}$ ($\text{X}=\text{Eu}$ or Ce ; $\text{Y}=\text{Dy}$ or Mn) and $\text{Na}_6(\text{SO}_4)_2\text{FCl}$ (doped with Dy , Ce or Eu) were prepared using a solid-state diffusion method. The mechanism of energy transfer from $\text{Eu}^{(2+)} \rightarrow \text{Dy}^{(3+)}$, $\text{Ce}^{(3+)} \rightarrow \text{Dy}^{(3+)}$ and $\text{Ce}^{(3+)} \rightarrow \text{Mn}^{(2+)}$ has also been studied. $\text{Dy}^{(3+)}$ emission in the host at 475 and 570 nm is observed due to $(4) \text{F}9/2 \rightarrow (6) \text{H}15/2$ and $(4) \text{F}9/2 \rightarrow (6) \text{H}13/2$ transition, whereas the PL emission spectra of $\text{Na}_6(\text{SO}_4)_2\text{FCl}:\text{Ce}$ phosphor shows $\text{Ce}^{(3+)}$ emission at 322 nm due to $5d \rightarrow 4f$ transition of the $\text{Ce}^{(3+)}$ ion. The main property of KCaSO_4Cl is its very high sensitivity, particularly when doped by Dy , Mn or Pb activators. This review also discusses the PL characteristics of some new phosphors such as LiMgSO_4F , $\text{Na}_6\text{Pb}_4(\text{SO}_4)_6\text{Cl}_2$, $\text{Na}_2\text{Mg}(\text{SO}_4)_{10}\text{Cl}_3$ and $\text{Na}_{15}(\text{SO}_4)_5\text{F}_4\text{Cl}$ (Figure 3).

CONCLUSION

In summary, the exploration of dysprosium-doped halosulfate compounds has underscored their significant potential in microelectronic applications due to their unique luminescent properties. Through systematic analysis of photoluminescence and energy transfer mechanisms, findings indicate that the effective doping concentrations directly influence the spectroscopic behavior of these materials,

enabling fine-tuning of their emission characteristics. The comparison with other luminescent materials, such as the sodium mixed sulphate phosphors which exhibit varying emission tones with specific rare-earth ion doping, reinforces the versatility of dysprosium as a key dopant. Such findings, similarly observed in the enhancing behaviors of other hosts like LiF and sodium sulfates, illuminate promising paths for innovative microelectronic designs, particularly in developing efficient light-emitting diodes (LEDs) and advanced dosimeter applications, thereby establishing dysprosium-doped halosulphates as quintessential materials in the evolving field of phosphor technology.

Dysprosium-doped halo-sulphate compounds offer great promise for an extensive number of future applications, especially in the microelectronic and solid-state lighting arenas. The characteristics of these materials that allow unique luminescence properties because of the dysprosium ion incorporation suggest that the use of light-emitting devices, such as LEDs, can be enhanced through increased efficiency and/or the ability to vary the emission spectra. Consequently, at a time where the demand for sustainability in energy becomes critical, such compounds are expected to lead to innovative applications in solar energy harvesting and photonic devices since they have the ability to convert and emit light efficiently. Also, the temperature dependent luminescence phenomena of dysprosium doped halosulphates could be turned into a lucrative technology for temperature sensing; these types of applications require very precise measurements. Thus, further investigations on these materials will enhance the understanding of luminescence behavior while paving the way to developing new technologies that solve modern energy challenges.

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