

RED-EMITTING TELLURITE GLASSES: A COMBINED INVESTIGATION OF PHYSICAL, STRUCTURAL, OPTICAL AND LUMINESCENCE PROPERTIES FOR POTENTIAL WLEDs AND SCINTILLATION APPLICATIONS

Patarawagee Yasaka^{1,2*}, Winut Wongwan^{1,2}, Kitipun Booin^{1,2} and Jakrapong Kaewkhao^{1,2}

Received: August 14, 2024; Revised: December 16, 2024; Accepted: March 19, 2025

Abstract

This study explores the influence of varying Europium oxide (Eu_2O_3) concentrations on the physical, structural, optical, and luminescence properties of boro-tellurite glasses. Glass samples were synthesized via the melt-quenching technique with Eu_2O_3 concentrations ranging from 0 to 3 mol%. Analytical techniques, including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and photoluminescence (PL) spectroscopy, were employed. Results revealed an increase in density and decreased molar volume with higher Eu_2O_3 content, indicating network expansion due to the larger ionic radius of Eu^{3+} ions. FTIR confirmed the presence of BO_3 and BO_4 units, with increased BO_4 proportions suggesting the role of Eu^{3+} ions as network modifiers. Photoluminescence studies showed characteristic emissions of Eu^{3+} ions, with the maximum intensity observed at 1.5 mol% Eu_2O_3 before concentration quenching occurred. Judd-Ofelt analysis demonstrated high asymmetry in the Eu^{3+} local environment, while CIE chromaticity coordinates highlighted a reddish-orange hue, suitable for white light-emitting diode (WLED) applications. X-ray-induced luminescence showed patterns consistent with photoluminescence, with the 1.5 mol% sample achieving 27.48% scintillation efficiency compared to a bismuth germanate (BGO) crystal. These findings underline the potential of Eu^{3+} -doped glasses as gain media for lasers and as phosphors for WLEDs, especially in indoor lighting and scintillation applications.

Keywords: Eu^{3+} ions; Glass material; Luminescence; Scintillator

¹ Center of Excellence in Glass Technology and Materials Science (CEGM), Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand. E-mail: pyasaka@webmail.npru.ac.th*, winutwongwan@gmail.com, kboonin@webamil.npru.ac.th, jakrapong@webamil.npru.ac.th

² Physics Program, Faculty of Science and Technology, Nakhon Pathom Rajabhat University, 73000, Thailand. E-mail: pyasaka@webmail.npru.ac.th*, winutwongwan@gmail.com, kboonin@webamil.npru.ac.th, jakrapong@webamil.npru.ac.th

* Corresponding author

DOI: <https://doi.org/10.55766/sujst6188>

Introduction

The increasing global demand for energy-efficient and eco-friendly lighting solutions has propelled the exploration of innovative materials for white light-emitting diodes (WLEDs) (Hong *et al.*, 2019). WLEDs offer numerous advantages over conventional lighting options, such as incandescent and fluorescent lamps, including superior luminous efficacy, extended operational lifespan, and reduced energy consumption (Khan *et al.*, 2019). The predominant method for generating white light in WLEDs involves integrating a blue or near-ultraviolet (n-UV) LED chip with phosphor materials. These phosphors convert a portion of the emitted light into longer wavelengths, producing a broad spectrum that the human eye perceives as white light (Stambouli *et al.*, 2013). The selection of phosphor materials is crucial in determining the color quality, luminous efficacy, and overall stability of WLEDs (Melo *et al.*, 2016). Rare-earth-doped glasses have emerged as promising contenders for WLED phosphors due to their exceptional optical attributes, chemical stability, and ease of fabrication (Boonin *et al.*, 2020). Among the various rare-earth ions, trivalent europium (Eu^{3+}) stands out due to its distinctive reddish-orange emission, arising from $^5\text{D}_0 \rightarrow ^7\text{F}_j$ transitions (Noorazlan *et al.*, 2013). The ability to tailor the intensity and spectral distribution of Eu^{3+} emission by modifying the host glass composition and Eu^{3+} ion concentration allows for precise control over the color characteristics of WLEDs (Zhang *et al.*, 2021). The incorporation of Eu^{3+} ions into glass matrices offers several benefits, including high quantum efficiency, prolonged luminescence lifetimes, and commendable thermal stability (Karthikeyan *et al.*, 2017). Furthermore, the amorphous nature of glasses facilitates the homogeneous distribution of Eu^{3+} ions, thereby minimizing concentration quenching and ensuring uniform luminescence (Gaafar and Marzouk, 2007). The selection of the glass host is crucial in optimizing the luminescence properties of Eu^{3+} -doped glasses. Tellurite glasses have garnered considerable interest due to their unique combination of high refractive index, low phonon energy, and excellent chemical durability (Zhou *et al.*, 2008). The high refractive index of tellurite glasses enhances the radiative transition probability of Eu^{3+} ions, resulting in improved luminescence efficiency (Zaman *et al.*, 2016). The low phonon energy of these glasses minimizes non-radiative relaxation processes, further contributing to the high quantum yield of Eu^{3+} emission (Rajesh *et al.*, 2020). Additionally, the excellent chemical

durability of tellurite glasses ensures the long-term stability of WLEDs under various operating conditions. In this present study, we delve into the fabrication and characterization of Eu^{3+} -doped tellurite glasses, investigating their potential for applications in reddish-orange lasers and WLEDs. A series of glasses with varying Eu_2O_3 concentrations were synthesized using the melt-quenching technique. The physical, structural, and luminescence properties of these glasses were meticulously examined using a combination of characterization techniques, including X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), and photoluminescence (PL) spectroscopy. The Judd-Ofelt (JO) theory was employed to analyze the local environment and bonding of Eu^{3+} ions within the glass matrix. Furthermore, the colorimetric properties of the glasses, including CIE coordinates and color correlated temperature (CCT), were assessed to evaluate their suitability for WLED applications. This investigation provides valuable insights into the interplay between composition, and structure affect the luminescence properties of Eu^{3+} -doped tellurite glasses. This could lead to the development of efficient and color-tunable WLED phosphors.

Experiment

The boro-tellurite glass samples investigated in this research were formulated with the chemical composition $(35-x)\text{TeO}_2: 30\text{ZnO}: 30\text{B}_2\text{O}_3: 5\text{BaO}: x\text{Eu}_2\text{O}_3$. The concentration of Europium oxide (Eu_2O_3), represented by “x”, was systematically varied at 0.00, 0.50, 1.00, 1.50, 2.00, and 3.00 mol% to examine its influence on the glass properties. The glass preparation involved thoroughly mixing the chemical constituents within alumina crucibles, followed by melting in an electric furnace maintained at $1,000^\circ\text{C}$. To alleviate internal stresses and enhance stability, the resulting glass samples underwent an annealing process at 300°C for a duration of 3 h. Subsequently, they were gradually cooled to ambient temperature. The prepared glasses were then meticulously cut and polished to achieve dimensions of $1\text{ cm} \times 1.5\text{ cm} \times 0.3\text{ cm}$. These precisely dimensioned samples were subsequently used for a comprehensive array of measurements encompassing physical, structural, optical, photoluminescence, and X-ray luminescence properties, as illustrated in Figure 1.

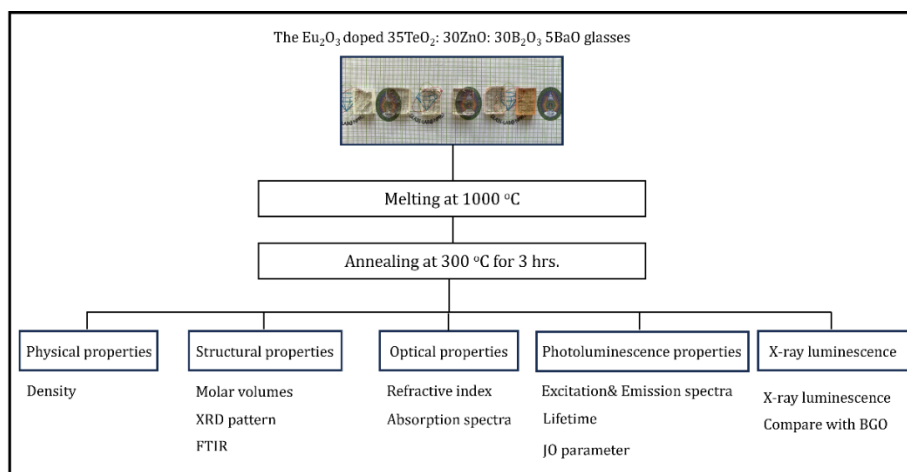


Figure 1. Schematic of synthesis and measurements of prepared glasses

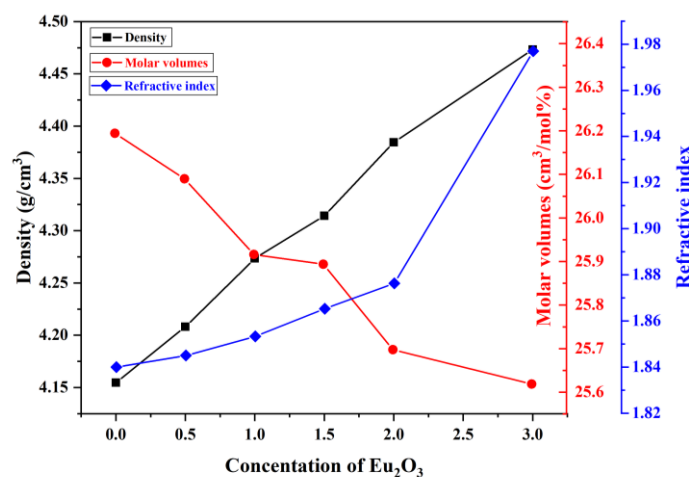


Figure 2. The density, molar volume, and refractive index of prepared glasses

Results and Discussion

Physical Properties

The physical properties of the fabricated glasses, including density and molar volume, were investigated to understand the structural changes induced by the varying Eu_2O_3 content as shown in Figure 2. The density of the glasses was measured using the Archimedes principle, with distilled water as the immersion liquid. The molar volume was then calculated based on the measured density and the chemical composition of the glasses. The results indicate that the density of the glasses increases while the molar volume decreases with the increasing concentration of Eu_2O_3 . This observation suggests that the addition of Eu_2O_3 leads to the expansion of the glass network, which can be attributed to

the larger ionic radius of Eu^{3+} ions compared to the other constituents in the glass matrix (Rao *et al.*, 2009). The sample's refractive index increases with the concentration of Eu_2O_3 , which corresponds to the density values as described by the equation $n=c/v$.

Amorphous Characterization and Fourier Transform Infrared Structural Characterizations (XRD and FTIR)

The structural properties of the glasses were characterized using X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR). XRD analysis confirmed the amorphous nature of all the prepared glasses, as evidenced by the absence of sharp diffraction peaks in the XRD patterns, as shown in Figure 3. The FTIR spectra revealed

the presence of characteristic vibrational bands associated with the different structural units in the glass network, as shown in Figure 4 and Table 1. The bands observed at around 450-500 cm^{-1} and 600-750 cm^{-1} are attributed to the bending vibrations of TeO_4 and TeO_3 units, respectively (Karthikeyan *et al.*, 2017). The band at around 800-1,000 cm^{-1} corresponds to the stretching vibrations of B-O bonds in BO_3 and BO_4 units (Gaafar and Marzouk, 2007). The intensity of the band associated with BO_4 units increases with the increasing concentration of Eu_2O_3 , suggesting the conversion of BO_3 units to BO_4 units. This structural modification can be attributed to the network modifier role of Eu^{3+} ions, which create

additional oxygen ions in the glass matrix, leading to the formation of more BO_4 units (Zhou *et al.*, 2008).

Table 1. The Fourier transforms infrared spectra and vibrational groups

Wavenumber (cm^{-1})	Assignment
660	The stretching vibrations of Te-O bond in $\text{TeO}_3/\text{TeO}_4$
909	The stretching vibrations of B-O bonds in BO_4 tetrahedra
1,233 and 1,351	The vibrations of pyroborate and orthoborate bridge

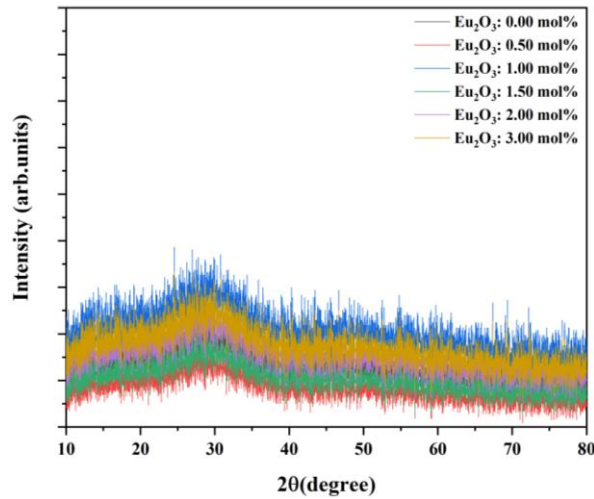


Figure 3. The XRD patterns of the prepared glasses

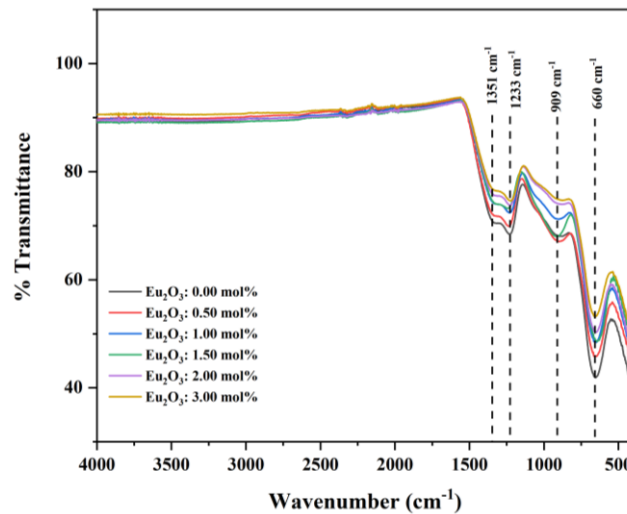


Figure 4. FTIR spectra of prepared glasses in the range of 400-4,000 cm^{-1}

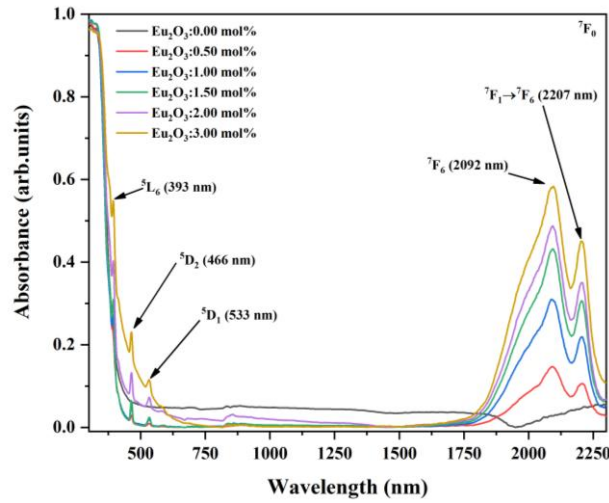


Figure 5. The absorption spectra of Eu_2O_3 doped glasses

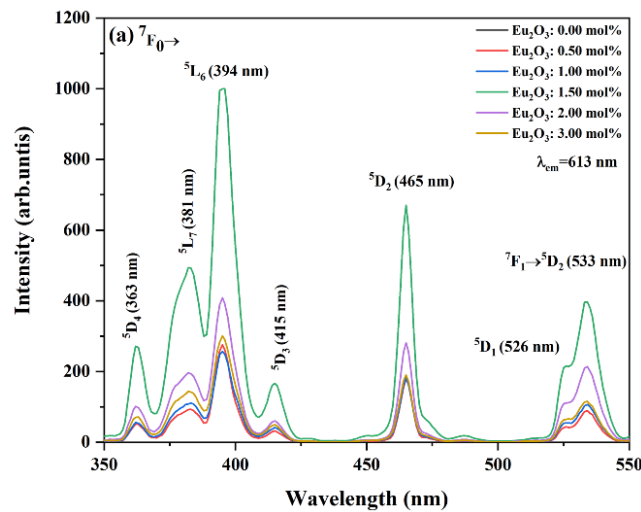


Figure 6. The excitation spectra of various concentration of Eu_2O_3 doped glasses

Absorption Spectra of Various Concentration of Eu_2O_3 Doped Glasses

The absorption spectra of the glasses were measured across the UV-VIS and NIR regions, as depicted in Figure 5. The observed absorption transitions correspond to f-f transitions that occur between the ground state $^7\text{F}_0$ and the thermally populated first excited state $^7\text{F}_1$. In the Eu_2O_3 -doped boro-tellurite glasses, five distinct transitions were identified within the UV-VIS region: $^7\text{F}_0 \rightarrow ^5\text{L}_6$ (393 nm), $^5\text{D}_2$ (466 nm), $^5\text{D}_1$ (533 nm), $^7\text{F}_6$ (2,092 nm), and $^7\text{F}_1 \rightarrow ^7\text{F}_6$ (2,207 nm). In contrast, only two transitions were observed in the NIR region (Khan *et al.*, 2019). Furthermore, a clear trend was noted where the absorbance of the prepared glasses

increased proportionally with the rising concentration of Eu_2O_3 .

Photoluminescence Properties

The room temperature excitation spectra for Eu^{3+} ion-doped glasses, spanning the 350 to 550 nm range, are presented in Figure 6. The spectra reveal seven distinct excitation peaks located at 363, 381, 394, 415, 465, 526, and 533 nm. These peaks are attributed to the electronic transitions from the $^7\text{F}_0$ ground state to the excited states $^5\text{D}_4$, $^5\text{L}_7$, $^5\text{L}_6$, $^5\text{D}_3$, $^5\text{D}_2$, $^5\text{D}_1$, and from $^7\text{F}_1$ to $^5\text{D}_2$, respectively. The most prominent peak, situated at 394 nm, was selected as the excitation wavelength for the subsequent investigation of the emission spectra, illustrated in

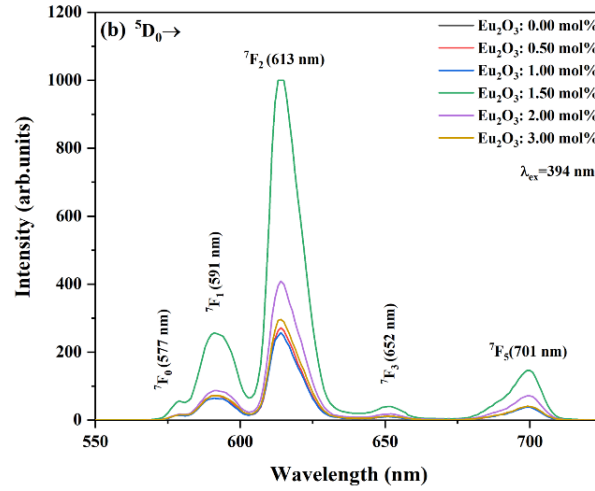


Figure 7. The emission spectra of various concentration of Eu_2O_3 doped glasses

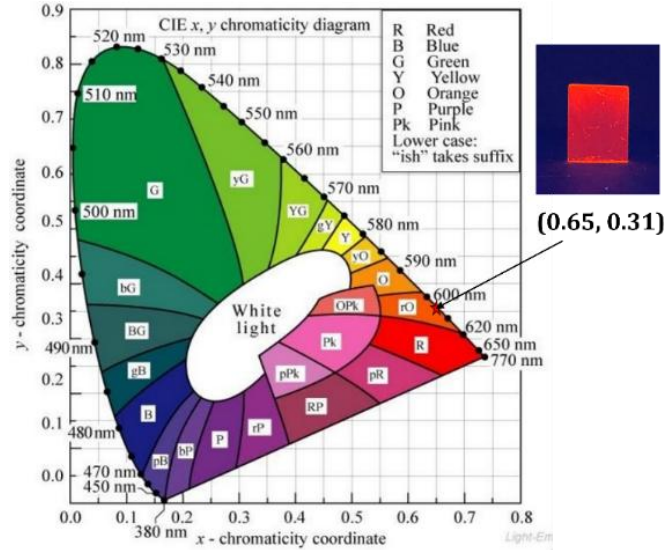


Figure 8. The CIE chromaticity diagram of 1.50 mol% Eu_2O_3 doped glass

Figure 7. The emission spectra consistently displayed five emission bands, which correspond to the following transitions of Eu^{3+} ions: $^5\text{D}_0 \rightarrow ^7\text{F}_0$ (577 nm), $^7\text{F}_1$ (591 nm), $^7\text{F}_2$ (613 nm; red), $^7\text{F}_3$ (652 nm), and $^7\text{F}_5$ (701 nm). The intensity of the emission spectrum exhibited an initial increase with the rising Eu_2O_3 concentration, reaching a maximum at 1.50 mol%. Beyond this point, a decrease in emission intensity was observed, indicative of a quenching phenomenon. The quenching effect in glass materials is attributed to non-radiative energy transfer mechanisms, such as cross-relaxation and resonant energy transfer. The increase in Eu^{3+} ion concentration results in a reduction of the inter-ionic distance between

Eu^{3+} ions, consequently enhancing the probability of energy transfer via cross-relaxation (Zaman *et al.*, 2016). The CIE chromaticity diagram (Commission Internationale de l'Eclairage 1931) for the Eu_2O_3 : 1.50 mol% doped glass is depicted in Figure 8. The color coordinates, computed from the emission spectra, were determined to be (0.65, 0.31), which corresponds to a reddish-orange hue. The luminescence lifetime measurements for the Eu^{3+} ion-doped zinc barium boro-tellurite glasses were conducted under 394 nm excitation, targeting the $^5\text{D}_0$ energy level of Eu^{3+} ions. The results are presented in Figure 9. It was observed that the luminescence lifetime of the $^5\text{D}_0$ excited level of Eu^{3+} in the prepared glass decreased with increasing

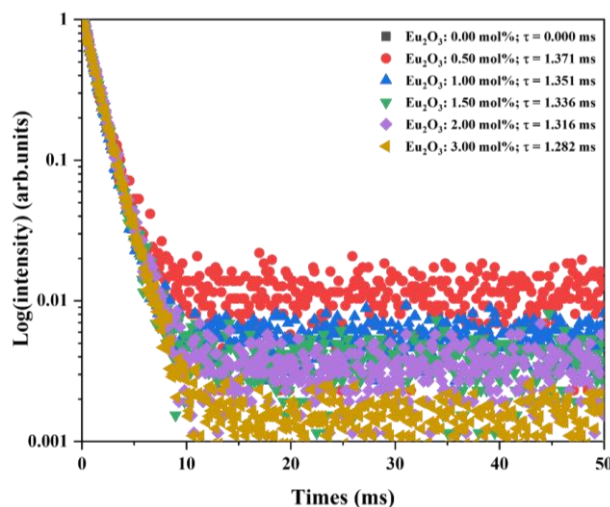


Figure 9. The luminescence lifetime of various concentration of Eu_2O_3 doped glasses

Table 2. The oscillator strength and Judd-Ofelt parameters Ω_λ ($\lambda=2, 4, 6$) with and without thermal correction

Transitions	Energies (cm^{-1})	Wavelength (nm)	Oscillator strengths			
			Without thermal		With thermal	
			$f_{\text{exp}} (\times 10^{-6})$	$f_{\text{cal}} (\times 10^{-6})$	$f_{\text{exp}} (\times 10^{-6})$	$f_{\text{cal}} (\times 10^{-6})$
${}^7\text{F}_1 \rightarrow {}^5\text{L}_6$	25,380.71	394	1.1613	1.1613	0.8013	0.8013
${}^7\text{F}_0 \rightarrow {}^5\text{D}_2$	21,505.38	465	0.2996	0.2235	0.2067	0.1542
${}^7\text{F}_1 \rightarrow {}^5\text{D}_1$	18,691.59	535	0.2041	0.2109	0.1408	0.1455
${}^7\text{F}_1 \rightarrow {}^7\text{F}_6$	4,780.11	2,092	3.2974	0.2588	2.2752	0.3599
${}^7\text{F}_0 \rightarrow {}^7\text{F}_6$	4,541.33	2,202	0.2042	0.2128	0.0633	0.2959
δ_{rms}			0.047		0.863	
$\Omega_2 (\times 10^{-20})$			6.667		4.674	
$\Omega_4 (\times 10^{-20})$			57.380		39.522	
$\Omega_6 (\times 10^{-20})$			0.1943		0.2702	

Eu^{3+} ion concentration. This decrease is attributed to the increased energy transfer between Eu^{3+} ions at higher concentrations (Rajesh *et al.*, 2020).

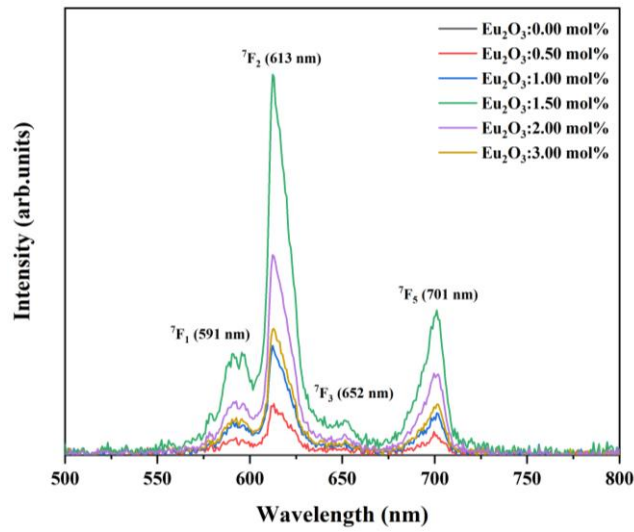
Judd-Ofelt Analysis and Thermal Corrections

The glass sample with 1.5 mol% Eu_2O_3 , which exhibits the highest emission intensity, was selected for the determination of Judd-Ofelt (JO) parameters and the application of thermal corrections. The JO theory was used to analyze the experimentally measured oscillator strengths, which led to the calculation of the JO intensity parameters (Ω_2 , Ω_4 , and Ω_6). The intensities of the absorption bands were quantified through experimental oscillator strengths (f_{exp}), which were calculated using the expression detailed in Ref. (Rao *et al.*, 2009). The resulting oscillator strengths for the prepared glasses are summarized in Table 2. For trivalent Europium ions, the energy gap between the ground state and the first excited state is relatively narrow. This requires the implementation

of a thermal correction to ensure the accurate determination of the oscillatory strength values (Rajesh *et al.*, 2020). The root mean square deviation (δ_{rms}) was computed both with and without the thermal correction, yielding values of 0.047 and 0.863, respectively. The low δ_{rms} value signifies a strong correlation between the experimental and theoretical oscillator strengths. In the Eu^{3+} -doped zinc barium boro-tellurite glasses, the JO parameters followed the trend $\Omega_4 > \Omega_2 > \Omega_6$. The magnitudes of Ω_4 and Ω_6 are indicative of bulk properties of the host glass, such as viscosity and rigidity. Conversely, the Ω_2 parameter is highly influenced by the local structural arrangement and composition surrounding the Eu^{3+} ions. The observed trend in JO parameters suggests that the glass samples exhibit a relatively loose structural network, and the Eu^{3+} ions are situated in environments with a notable degree of asymmetry (Rao *et al.*, 2009).

Table 3. The radiative properties with and without thermal correction

Transitions	Energies (cm ⁻¹)	Wavelength (nm)	Radiative properties							
			Without thermal				With thermal			
			A _R (s ⁻¹)	σ (×10 ⁻²⁰) cm ²	β _{Rcal}	β _{Resp}	A _R (s ⁻¹)	σ (×10 ⁻²⁰) cm ²	β _{Rcal}	β _{Resp}
⁷ F ₁ → ⁵ L ₆	17,331	394	0.00	0.0000	0.0132	0.0000	0.00	0.0000	0.0132	0.0000
⁷ F ₀ → ⁵ D ₂	16,920	465	90.63	429.8800	0.1924	0.0394	90.63	429.8800	0.1924	0.0561
⁷ F ₁ → ⁵ D ₁	16,313	535	421.81	25.7420	0.6810	0.7772	291.04	17.7610	0.6810	0.7632
⁷ F ₁ → ⁷ F ₆	15,361	2,092	0.00	0.0000	0.0188	0.0000	0.00	0.0000	0.0188	0.0000
⁷ F ₀ → ⁷ F ₆	14,306	2,202	1788.68	1.8981	0.0947	0.1834	1,232.00	1.3074	0.0947	0.1807
τ _{rad} (ms)			0.434				0.619			

**Figure 10.** The X-ray-induced luminescence of 1.50mol%Eu₂O₃ doped glass

Radiative Properties

The Judd-Ofelt intensity parameters, as shown in Table 3, were used to evaluate several radiative properties, such as the radiative transition probability, radiative branching ratio, and stimulated emission cross-section. The experimental branching ratios were obtained by examining the integral intensity of emission lines originating from a specific excited state. These experimental values were then compared to the theoretical branching ratios calculated based on Judd-Ofelt theory. The branching ratio provides a measure of how the emissive transitions are distributed within the emission spectrum. A branching ratio greater than 0.5 suggests that most of the emission radiation is concentrated in that particular transition, indicating its potential for laser applications. As shown in Table 3, the ⁵D₀→⁷F₂ transitions demonstrate the highest radiative transition rates among all the observed transitions, making them particularly suitable for laser action (Khan *et al.*, 2019).

X-ray Induced Luminescence

The X-ray induced luminescence spectra, obtained under irradiation at 50 kV and 30 mA, are presented in Figure 10. The spectra exhibit a pattern consistent with the photoluminescence emission spectra. The samples demonstrate X-ray induced luminescence signals characterized by sharp emission peaks at 591, 613, 652, and 701 nm, which are attributed to the ⁴f-⁴f transitions of Eu³⁺ ions. The most intense signal is observed in the Eu₂O₃: 1.5 mol% sample, centered at a wavelength of 613 nm, aligning with the emission spectra (Eu₂O₃ 1.5 mol%). To assess the scintillation properties, the scintillation efficiency of the Eu₂O₃: 1.5 mol% sample was compared to that of a bismuth germanate (BGO) scintillator crystal. The total area under all peak spectra was calculated to represent the integral scintillation efficiency of the Eu₂O₃: 1.5 mol% sample. The analysis revealed that the prepared glass exhibited a scintillation efficiency equivalent to 27.48% of the BGO scintillator crystal, as illustrated in Figure 11.

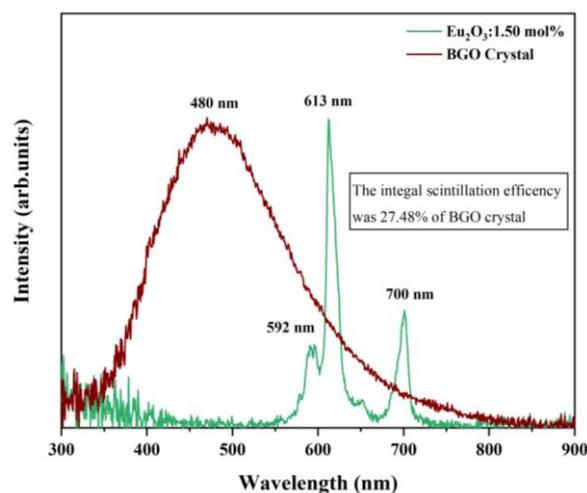


Figure 11. The X-rays induced luminescence spectra of Eu_2O_3 : 1.5 mol% doped glass compared with the BGO crystal scintillator

This result suggests that the developed glass holds promising potential for applications in the field of scintillation.

Conclusions

The present investigation has successfully demonstrated the fabrication of Eu^{3+} -doped borotellurite glasses via the melt-quenching technique. The study comprehensively analyzed the influence of varying Eu_2O_3 concentrations on the physical, structural, and luminescence properties of these glasses. The observed increase in density and decrease in molar volume with higher Eu_2O_3 content point towards the expansion of the glass structure due to the larger ionic radius of Eu^{3+} ions. FTIR analysis confirmed the presence of BO_3 and BO_4 units, with the latter increasing in proportion to Eu_2O_3 concentration, suggesting a network modifier role for Eu^{3+} ions. The optical absorption spectra revealed characteristic f-f transitions of Eu^{3+} ions, and the calculated optical band gap energy decreased with increasing Eu_2O_3 content, implying the creation of additional energy levels within the band gap. Judd-Ofelt analysis indicated a higher degree of asymmetry and covalency in the Eu^{3+} site with increasing Eu_2O_3 concentration. The photoluminescence spectra showcased characteristic emission bands of Eu^{3+} ions, with the intensity initially increasing with Eu_2O_3 concentration up to 1.50 mol%, followed by concentration quenching. The CIE coordinates shifted towards the reddish-orange region with increasing Eu_2O_3 , and the correlated color temperature decreased, suggesting warmer color tones suitable for indoor

lighting. The X-ray induced luminescence spectra exhibited a similar pattern to the photoluminescence spectra, and the Eu_2O_3 : 1.5 mol% sample showed promising scintillation efficiency. The findings of this study highlight the potential of Eu^{3+} -doped borotellurite glasses as gain media for reddish-orange lasers and as phosphors for WLEDs, particularly for indoor lighting applications. The tunability of their luminescence properties through Eu_2O_3 concentration adjustments further underscores their versatility for diverse photonic applications.

Acknowledgment

P. Yasaka would like to thank Nakhon Pathom Rajabhat University for supporting this research. The authors thank the Center of Excellence in Glass Technology and Materials Science (CEGM) for the measurement instrument.

References

- Boonin, K., Yasaka, P., Limkitjaroenporn, P., Rajaramakrishna, R., Askin, A., Sayyed, M.I., Kothan, S., and Kaewkhao, J. (2020). Effect of BaO on lead free zinc barium tellurite glass for radiation shielding materials in nuclear application. *Journal of Non-Crystalline Solids*, 550:120386. <https://doi.org/10.1016/j.jnoncrysol.2020.120386>
- Gaafar, M.S. and Marzouk, S.Y. (2007). Mechanical and structural studies on sodium borosilicate glasses doped with Er_2O_3 using ultrasonic velocity and FTIR spectroscopy. *Physica B: Condensed Matter*, 388(1-2): 294-302. <https://doi.org/10.1016/j.physb.2006.06.132>
- Hong, K.S., Kim, M., Ha, M.G., Kim, J.P., Yoon, J.H., Kim, J.H., Yang, H.S., and Kim, H.G. (2019). Red-emission properties and crystallization behavior in Eu_2O_3 - TeO_2

- glasses. *Journal of Non-Crystalline Solids*, 505:400-405. <https://doi.org/10.1016/j.jnoncrysol.2018.10.030>
- Karthikeyan, P., Vijayakumar, R., and Marimuthu, K. (2017). Luminescence studies on Dy^{3+} doped calcium borotellurite glasses for white light applications. *Physica B: Condensed Matter*, 521:347–354. <https://doi.org/10.1016/j.physb.2017.07.018>
- Khan, I., Rooh, G., Rajaramakrishna, R., Sirsittapokakun, N., Kim, H.J., Kaewkhao, J., and Kirdsiri, K. (2019). Energy transfer phenomenon of Gd^{3+} to excited ground state of Eu^{3+} ions in $\text{Li}_2\text{O-BaO-Gd}_2\text{O}_3\text{-SiO}_2\text{-Eu}_2\text{O}_3$ glasses. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*, 210:21–29. <https://doi.org/10.1016/j.saa.2018.11.008>
- Melo, G.H.A., Dias, J.D.M., Lodi, T.A., Barboza, M.J., Pedrochi, F., and Steimacher, A. (2016). Optical and spectroscopic properties of Eu_2O_3 doped CaBaI glasses. *Optical Materials*, 54:98-103. <https://doi.org/10.1016/j.optmat.2016.02.015>
- Noorazlan, A.M., Kamari, H.M., Zulkefly, S.S., and Mohamad, D.W. (2013). Effect of erbium nanoparticles on optical properties of zinc borotellurite glass system. *Nanomaterials*, 2013:Article 940917. <https://doi.org/10.1155/2013/940917>
- Rajesh, M., Reddy, G.R., Sushma, N.J., Devarajulu, G., and Raju, B.D.P. (2020). Phonon sideband analysis, structural and spectroscopic properties of Eu^{3+} ions embedded $\text{SiO}_2\text{-B}_2\text{O}_3\text{-CaF}_2\text{-NaF-Na}_2\text{O}$ glasses. *Optical Materials*, 107:110038. <https://doi.org/10.1016/j.optmat.2020.110038>
- Rao, A.S., Rao, B.R.V., Prasad, M.V.V.K.S., Kumar, J.V.S., Jayasimhadri, M., Rao, J.L., and Chakradhar, R.P.S. (2009). Spectroscopic and optical properties of Nd^{3+} doped fluorine containing alkali and alkaline earth zinc-aluminophosphate optical glasses. *Physica B: Condensed Matter*, 404(20):3570-3576. <https://doi.org/10.1016/j.physb.2009.06.114>
- Stambouli, W., Elhouichet, H., Gelloz, B., and Férid, M. (2013). Optical and spectroscopic properties of Eu-doped tellurite glasses and glass ceramics. *Journal of Luminescence*, 138:201-208. <https://doi.org/10.1016/j.jlumin.2013.01.019>
- Zaman, F., Kaewkhao, J., Rooh, G., Srisittipokakun, N., and Kim, H.J. (2016). Optical and luminescence properties of $\text{Li}_2\text{O-Gd}_2\text{O}_3\text{-MO-B}_2\text{O}_3\text{-Sm}_2\text{O}_3$ ($\text{MO}=\text{Bi}_2\text{O}_3, \text{BaO}$) glasses. *Journal of Alloys and Compounds*, 676:275-285. <https://doi.org/10.1016/j.jallcom.2016.03.176>
- Zhang, L., Sun, Q., Wang, J., Zhang, Z., Zhang, W., Wang, J., Chen, H., and Li, M. (2021). Effect of SrO content on microstructure of $\text{Bi}_2\text{O}_3\text{-B}_2\text{O}_3\text{-ZnO-BaO-SrO}$ low-melting glass frit and joining performance of soda lime glass substrates. *Journal of Alloys and Compounds*, 872:159707. <https://doi.org/10.1016/j.jallcom.2021.159707>
- Zhou, L., Lin, H., Chen, W., and Luo, L. (2008). IR and Raman investigation on the structure of $(100-x)\text{B}_2\text{O}_3\text{-}x[0.5\text{BaO-0.5ZnO}]$ glasses. *Journal of Physics and Chemistry of Solids*, 69(10):2499-2502. <https://doi.org/10.1016/j.jpcs.2008.05.013>