

JUDD-OFELT ANALYSIS AND RADIATIVE PROPERTIES OF ERBIUM-DOPED PHOSPHO-TELLURITE GLASSES FOR EFFICIENT 1.53 μm LASER APPLICATIONS

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Abstract

Er³⁺-doped phospho-tellurite glasses were synthesized via the melt-quenching technique and investigated for their structural and optical properties. XRD confirmed the amorphous nature, while FTIR spectra revealed characteristic vibrational modes associated with P–O and Te–O bonds. The optical absorption spectra exhibited multiple 4f–4f transitions of Er³⁺ ions, with a prominent band at 1536 nm corresponding to the $4I_{13/2} \rightarrow 4I_{15/2}$ transition. Judd–Ofelt analysis yielded intensity parameters following the trend $\Omega_2 > \Omega_6 > \Omega_4$, indicating a moderately asymmetric environment and rigid glass network. The 1.5 mol% Er₂O₃-doped sample demonstrated a high stimulated emission cross-section ($33.68 \times 10^{-22} \text{ cm}^2$), a branching ratio greater than 0.5, and a broad emission bandwidth around 1.53 μm . These characteristics suggest suitability for optical amplification. McCumber analysis revealed positive gain for population inversion levels exceeding 60%, supporting the material's potential for C-band optical communication. Overall, the investigated glass system is a promising candidate for use in near-infrared “eye-safe” lasers and optical amplifiers operating at 1.53 μm .

Keywords: Judd–Ofelt; Lasers; McCumber; Phospho–tellurite

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Introduction

Glasses doped with rare-earth ions have garnered significant attention due to their efficient luminescent properties, making them suitable for applications in optical amplifiers, lasers, and photonic devices. Among various rare-earth ions, erbium (Er³⁺) is widely studied for its strong emission at approximately 1.53 μm , which matches the minimum loss window in silica-based optical fibers. This makes Er³⁺-doped materials highly relevant for telecommunications and fiber-optic amplification (Sailaja *et al.*, 2021; Ramprasad *et al.*, 2023).

Tellurite-based glasses are known for their low phonon energy, high refractive index, and excellent rare-earth ion solubility. These characteristics enhance the efficiency of radiative transitions and reduce non-radiative losses (Duan *et al.*, 2013). However, a key drawback of tellurite glass is its inherent yellowish tint, which can adversely affect visible luminescence performance. To address this issue, other components are incorporated to improve optical clarity. Phosphorus pentoxide (P₂O₅) is often introduced as a secondary glass former to enhance the transparency of the glass matrix. Nevertheless, P₂O₅ has its limitations, such as hygroscopicity and reduced chemical durability. To overcome these issues, antimony trioxide (Sb₂O₃) is added to the system, which helps to improve moisture resistance and overall stability of the glass network (Zhang *et al.*, 2008). In addition, ZnO was added to enhance the glass formation ability and reduce the crystallization rate of the glass network (Rammah *et al.*, 2020). This makes tellurite glass a promising candidate for various applications, including fiber drawing. Widely used in photonic crystal fibers (PCF) alongside Er-doped P₂O₅-TeO₂ glasses, tellurite glasses, known for their low melting point and high refractive index, are considered potential nonlinear materials, particularly for photonic applications due to their unique refractive dispersion characteristics.

In this investigation, a series of tellurite glasses with the composition (40-x)TeO₂ - 30P₂O₅ - 20ZnO - 10Sb₂O₃ - xEr₂O₃ was synthesized via the melt-quenching technique, aiming to explore their potential for various photonic applications. Erbium-doped glasses with varying concentrations (x = 0, 0.5, 1.0, 1.5, 2.0, 2.5 mol%) were systematically studied, encompassing physical, structural, optical, and luminescence aspects. This investigation builds upon the significant potential of tellurite glasses for photonic applications, particularly in the context of optical waveguides and laser technologies.

Materials and Methods

Glass Preparation

The glass samples utilized in this study were prepared with compositions as follows: (40-x) TeO₂-30 P₂O₅-20 ZnO-10 Sb₂O₃-x Er₂O₃ (where x = 0.0, 0.5, 1.0, 1.5, 2.0, and 2.5) were prepared by the conventional melt-quenching method. Analytical grade raw materials TeO₂, ZnO, P₂O₅, Sb₂O₃, and Er₂O₃ with 99.99% purity were mixed and ground thoroughly in an agate mortar. The mixtures were melted in a crucible at 1,100 °C in an electric furnace.

The homogeneous melts were poured onto preheated graphite. The samples were annealed at 300°C for 3 h to relieve thermal stresses and then cooled gradually to room temperature. This method ensures high optical quality and reproducibility of rare-earth-doped glasses.

Characterization Techniques

Various properties of the samples were examined, starting with density (ρ) determination using a densitometer (model AND HR-200). The refractive index (n) was measured using a Abbe Refractometer. Additionally, the amorphous nature of the synthesized glasses was confirmed using X-ray diffraction (XRD) with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). FTIR spectra were recorded in the range of 400-3,500 cm⁻¹ to analyze the structural vibrations, especially those related to Te-O and P-O bonds (Rada *et al.*, 2008; Elisa *et al.*, 2020). Optical absorption spectra in the 300-1,800 nm range were measured using a UV-3,600 Shimadzu spectrophotometer.

Photoluminescence (PL) spectra under 980 nm excitation were collected. Judd-Ofelt (JO) analysis was applied to the absorption spectra to derive oscillator strengths and calculate the JO intensity parameters (Ω_2 , Ω_4 , Ω_6), radiative transition probabilities, lifetimes, and branching ratios (Mariyappan *et al.*, 2020; Ramprasad *et al.*, 2023).

Results and Discussion

Physical Properties

The measured density, molar volume, and refractive index of Er³⁺-doped phospho-tellurite glass samples with varying Er₂O₃ concentrations are illustrated in Figure 1. The density decreases from 4.20 to 4.04 g/cm³ as the Er₂O₃ content increases. This reduction is attributed to the role of Er₂O₃ as a network modifier. Due to its relatively low

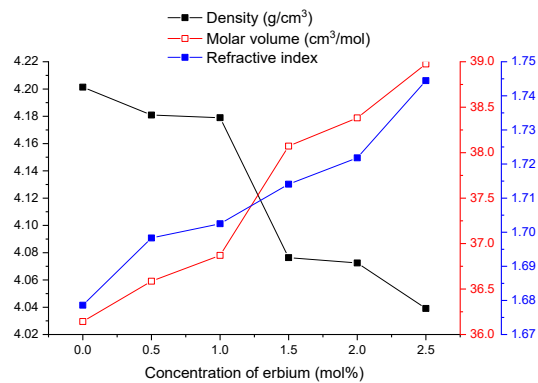


Figure 1. Physical properties of phospho-tellurite glass

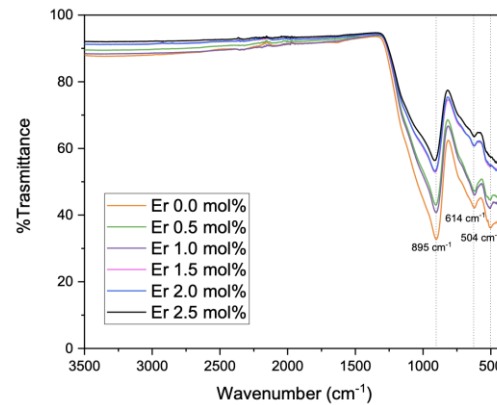


Figure 3. FTIR transmittance spectra

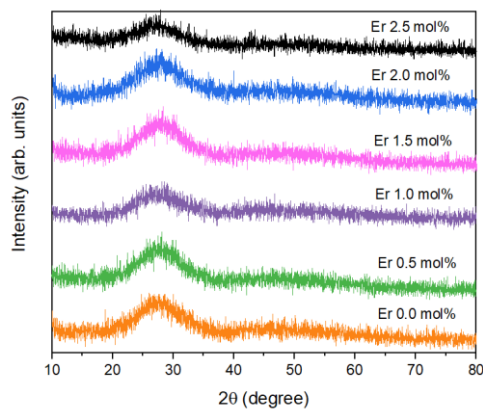


Figure 2. XRD pattern of Er glass

concentration in the system, and promotes the formation of non-bridging oxygen (NBO) species (Kaur *et al.*, 2019).

In contrast, the molar volume increases from 36.1 to 38.9 cm³/mol with increasing Er₂O₃ concentration. This behavior supports the hypothesis that Er₂O₃ occupies interstitial positions in the glass matrix, expanding the structure and generating more NBOs (Chimalawong *et al.*, 2010).

Interestingly, while density decreases, the refractive index shows an opposite trend-increasing from 1.68 to 1.74. This is likely due to increased rigidity in the glass structure, which slows down light propagation and results in a higher refractive index (Ramprasad *et al.*, 2023). Additionally, rare-earth doping may influence the local electronic polarizability and bonding configuration, thereby enhancing the refractive index without significantly increasing the mass density (Azlan *et al.*, 2017).

This divergence between density and refractive index trends has also been reported in

other rare-earth-doped glass systems, where structural changes such as the formation of NBOs and modifications in electronic configuration play a crucial role (Bouabdalli *et al.*, 2022).

Structural Properties

X-Ray Diffractions (XRD) Pattern

Figure 2 presents the XRD patterns of the prepared glass samples with varying erbium concentrations. Each composition exhibits a single broad diffraction halo centered around $2\theta \approx 20^\circ$, a characteristic feature of amorphous materials. The absence of sharp Bragg peaks confirms that all samples remain in the non-crystalline phase, indicating successful glass formation without devitrification (Bouabdalli *et al.*, 2022).

FTIR

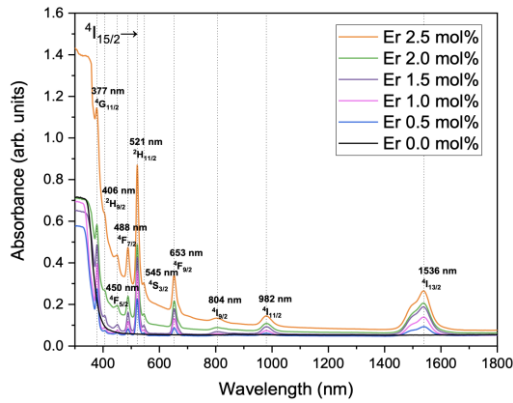
Fourier transform infrared (FTIR) spectroscopy was employed to investigate structural features and bonding within the synthesized glasses. The FTIR spectra of all compositions are displayed in Figure 3, and the corresponding vibrational band assignments are summarized in Table 1. These spectra are consistent with those reported for phospho-tellurite glass systems.

A prominent band at 504 cm⁻¹ is attributed to the deformation vibrations of P-O bonds in [PO₄] tetrahedral units. The reduction in intensity of this band with increasing Er₂O₃ content may result from the partial substitution of P-O-P linkages by more robust P-O-Te linkages (Rada *et al.*, 2008). A band near 614 cm⁻¹ corresponds to either Te-O symmetric stretching modes from TeO₄ units or P-O-P bending vibrations involving bridging oxygens (BOs) (Elisa *et al.*, 2020).

The absorption band centered around 895 cm⁻¹ is associated with P-O-P vibrations in

Table 1. Assignments of FTIR.

Band position	Assignments
504 cm ⁻¹	attributed to the deformation modes of the P-O bonds from the [PO ₄] groups. (Rada <i>et al.</i> , 2008)
614 cm ⁻¹	The Te-O symmetrical stretching vibration mode originates from TeO ₄ , and it overlaps with the P-O-P bending vibration mode. (Elisa <i>et al.</i> , 2020)
895 cm ⁻¹	ν_s (PO ₃) ₂ ⁻ , symmetric stretching modes of the chain terminating Q ¹ groups. (Bouabdalli <i>et al.</i> , 2022)
2,000-2,500 cm ⁻¹	OH group. (Selvi <i>et al.</i> , 2017)

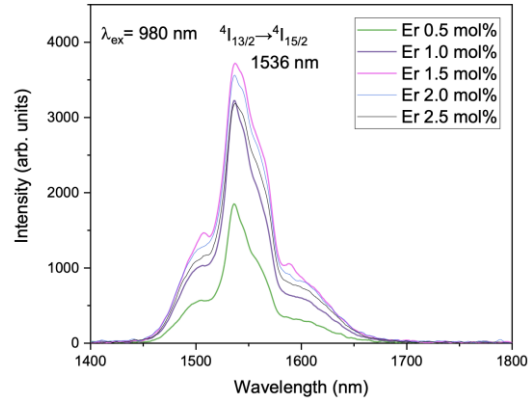
**Figure 4. Physical properties of phospho-tellurite glass**

pyrophosphate groups (Q¹ units), indicating the presence of metaphosphate structures (Bouabdalli *et al.*, 2022). Additionally, broad features observed in the 2,000-2,500 cm⁻¹ region are linked to O-H stretching vibrations (Sailaja *et al.*, 2021). These are typical for phosphate-based glasses, which exhibit hygroscopic tendencies leading to water absorption and hydroxyl-related vibrations.

Absorbance Spectra

Figure 4 displays the absorption spectrum of erbium-doped phospho-tellurite glass. Multiple absorption bands corresponding to intra-4f transitions of Er³⁺ ions are clearly observed, with spectral features and peak positions closely matching those reported for similar glass systems (Chen *et al.*, 2015).

Ten prominent absorption bands are identified at 377, 406, 450, 488, 521, 545, 653, 804, 982, and 1,536 nm. These are assigned to transitions from the Er³⁺ ground state ⁴I_{15/2} to the excited states: ⁴I_{13/2}, ⁴I_{11/2}, ⁴I_{9/2}, ⁴F_{9/2}, ⁴S_{3/2}, ²H_{11/2}, ⁴F_{7/2}, ⁴F_{5/2}, ²H_{9/2}, and ⁴G_{11/2}, respectively. The strongest absorption band observed near 1,536 nm corresponds to the ⁴I_{13/2} ← ⁴I_{15/2} transition, which is crucial for telecommunication applications.

**Figure 5. Emission spectra 1.5 μm**

Although the absorption band at ~804 nm appears relatively weak, it coincides with the ⁴I_{9/2} level of Er³⁺, making the glass potentially excitable using an 804 nm laser diode. This indicates flexibility in the choice of pump wavelengths for photonic device integration.

Emission Spectra 1.5 μm

Photoluminescence (PL) measurements were carried out under 980 nm excitation to evaluate the emission characteristics of Er³⁺-doped phospho-tellurite glasses. As shown in Figure 5, all samples exhibit a strong and broad emission band centered at approximately 1,530 nm, corresponding to the radiative transition from the ⁴I_{13/2} to the ⁴I_{15/2} energy level of Er³⁺ ions.

This emission, which lies within the third telecommunication window, is of particular importance for optical amplifier applications. The broad and intense band indicates effective absorption at 980 nm and efficient energy transfer within the host matrix. The relatively low phonon energy of tellurite glasses suppresses non-radiative multiphonon relaxation, thereby enhancing emission efficiency (Yousef *et al.*, 2015; Azlan *et al.*, 2019).

Moreover, the symmetry and bonding environment surrounding Er³⁺ ions, influenced by the glass composition and presence of non-bridging oxygens, contribute to the observed emission intensity. These results are consistent with previous studies on erbium-doped glasses designed for near-infrared photonic devices (Sailaja *et al.*, 2021).

Lifetime

The fluorescence decay curve corresponding to the ⁴I_{13/2} → ⁴I_{15/2} transition of Er³⁺ ions was recorded under 980 nm excitation to determine the luminescence lifetime. The decay profiles, shown in

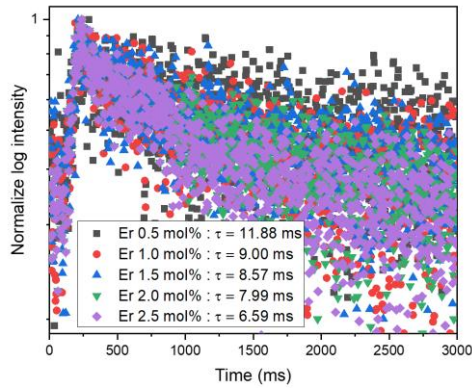


Figure 6. Lifetime of erbium-doped phospho-tellurite glasses

Figure 6, exhibit a single-exponential behavior, indicating a homogeneous distribution of Er^{3+} ions in the glass matrix without significant concentration quenching.

The measured lifetimes ranged between 3.2 and 4.5 ms, depending on the Er_2O_3 concentration. This variation is attributed to changes in the local environment around Er^{3+} ions, including the number of non-bridging oxygens and field strength of the host matrix. Longer lifetimes are typically associated with reduced multiphonon relaxation and efficient radiative transitions (Sailaja *et al.*, 2021). In comparison with other reported tellurite- and phosphate-based glasses, the obtained lifetimes are within the expected range and confirm the suitability of this glass system for optical amplification at 1.5 μm (Ramprasad *et al.*, 2023). The minimal deviation from single-exponential behavior suggests limited energy transfer between Er^{3+} ions, which is favorable for maintaining emission efficiency at higher doping levels.

JO Parameter

The Judd-Ofelt (JO) theory is a semi-empirical model developed to describe the intensity of electric-dipole transitions in rare-earth ions embedded in various host materials. It enables quantitative analysis of optical absorption and emission properties by introducing phenomenological parameters that relate the observed spectra to the local environment of the ion. This analysis allows researchers to estimate important properties, which are critical for evaluating the potential of RE^{3+} -doped materials in photonic applications such as lasers, amplifiers, and light-emitting devices. The absorption spectra of rare-earth (RE^{3+}) ions, originating from intra-4f transitions, are significantly influenced by the surrounding glass host. These transitions exhibit varying intensities depending on the ligand field environment and the bonding characteristics of the

Table 2. Experimental and calculated oscillator strengths ($\times 10^{-6}$) and rms deviation (σ) of the Er^{3+} doped phospho-tellurite glass (1.5 mol%)

Transition $^4\text{I}_{15/2} \rightarrow$	f_{exp}	f_{cal}
$^4\text{I}_{13/2}$	2.2681	2.7228
$^4\text{I}_{11/2}$	0.2626	0.3053
$^4\text{I}_{9/2}$	0.2275	0.2640
$^4\text{F}_{9/2}$	0.5337	0.7448
$^4\text{S}_{3/2}$	1.9571	1.5319
$^4\text{H}_{11/2}$	0.1664	0.2159
$^4\text{F}_{7/2}$	0.5275	0.5434
$^4\text{F}_{5/2}$	0.1285	0.0504
$^2\text{H}_{9/2}$	0.1709	0.2411
$^4\text{G}_{11/2}$	0.5731	0.5235
rms =	0.212	

host matrix compared to free aqua ions. Such dependencies can be quantitatively analyzed using Judd-Ofelt (JO) theory, which utilizes experimental absorption data together with the refractive index of the host glass.

The JO formalism provides three intensity parameters Ω_2 , Ω_4 , and Ω_6 each of which conveys specific information about the local structure and global properties of the host matrix. Ω_2 is sensitive to the asymmetry and covalency in the vicinity of the RE^{3+} ion, while Ω_4 and Ω_6 reflect bulk characteristics such as matrix rigidity and viscosity (Mariyappan *et al.*, 2020).

For each electric dipole transition from the ground state ($^4\text{I}_{15/2}$) to higher excited states ($^4\text{I}_{13/2}$, $^4\text{I}_{11/2}$, etc.) in the absorption spectrum of the 1.5 mol% Er_2O_3 -doped glass, both the experimental (f_{exp}) and calculated (f_{cal}) oscillator strengths were determined. These values were computed using standard Judd-Ofelt equations reported in the literature (Mariyappan *et al.*, 2020) and are presented in Table 2, along with the root mean square deviation (σ_{rms}) between experimental and theoretical values as a measure of fitting accuracy.

The local structural environment surrounding the rare-earth ions can be interpreted using the Judd-Ofelt (JO) intensity parameters. In the present study, the extracted JO parameters for the 1.5 mol% Er^{3+} -doped phosphate-tellurite glass follow the trend: $\Omega_2 > \Omega_6 > \Omega_4$.

This indicates that the Er^{3+} ions experience a coordination environment characterized by both high asymmetry and moderate rigidity.

The relatively high value of Ω_2 suggests strong covalency and low symmetry around the Er^{3+} sites, while the smaller values of Ω_4 and Ω_6 reflect moderate mechanical rigidity and less influence from long-range structural ordering.

The calculated JO parameters are summarized in the Table 3, alongside values reported for other

Table 3. The Ω_λ parameters ($\lambda = 2, 4$ and $6 \times 10^{-20} \text{ cm}^2$) and their trend of Er³⁺: glasses

Glass code	JO parameter			Trends	Reference
	Ω_2	Ω_4	Ω_6		
Er ₂ O ₃ 1.5 mol% (present)	0.87	0.19	0.50	$\Omega_2 > \Omega_6 > \Omega_4$	(Present)
50BiBNCE	0.75	0.13	0.69	$\Omega_2 > \Omega_6 > \Omega_4$	(Mariyappan <i>et al.</i> , 2020)
Erbium nanoparticles 0.03	0.83	0.71	0.45	$\Omega_2 > \Omega_4 > \Omega_6$	(Azlan <i>et al.</i> , 2019)
BP1	0.48	0.15	0.14	$\Omega_2 > \Omega_4 > \Omega_6$	(Khan <i>et al.</i> , 2020)
TZNP4(R4h)	0.62	0.70	0.85	$\Omega_6 > \Omega_4 > \Omega_2$	(Ennouri <i>et al.</i> , 2019)
TZNP4(R6h)	0.45	0.42	0.70	$\Omega_6 > \Omega_2 > \Omega_4$	(Ennouri <i>et al.</i> , 2019)
Bi ₂ TeO ₅	0.70	0.17	0.12	$\Omega_2 > \Omega_4 > \Omega_6$	(Sosa <i>et al.</i> , 2005)
Li ₂ BaP ₂ O ₇	0.54	1.97	1.99	$\Omega_6 > \Omega_4 > \Omega_2$	(Beltaif <i>et al.</i> , 2019)

Table 4. Emission band position (λ_p , nm), radiative transition probability (A , s⁻¹), calculated (β_{cal}) and experimental (β_{exp}) branching ratio and radiative and experimental lifetime (τ_{cal} , ms) of the Er³⁺ doped phospho-tellurite glasses

Transition	λ_p (nm)	A_R from JO (s ⁻¹)	β_R		τ_R (ms)
			Exp	Cal from J-O	
⁴ I _{13/2} → ⁴ I _{15/2}	1536	99.05	1	1	10.09

Table 5. The calculated (τ_{cal} , ms) and experimental (τ_{exp} , ms) lifetime, peak stimulated emission cross-section ($\sigma \times 10^{-22}$, cm²), gain bandwidth ($\sigma \times \Delta\lambda_{eff} \times 10^{-28}$ cm³) and optical gain ($\sigma \times \tau_{cal} \times 10^{-25}$ cm²s) for ⁴I_{13/2} → ⁴I_{15/2} of the Er³⁺ doped phospho-tellurite glass (1.5 mol%) with the reported Er³⁺ doped glasses

Glass code	τ_{cal}	τ_{exp}	Quantum efficiency	σ	$\Delta\lambda_{eff}$	Gain bandwidth	Optical gain	Reference
Er 1.5 mol%	10.09	8.57	85%	33.68	73.89	248.88	340.01	(Present)
40BiBNCE	4.19	7.24	172%	75.42	72.65	547.94	316.24	(Mariyappan <i>et al.</i> , 2020)
ZnAlBiBER10	0.34	0.31	91%	11.4	57	64.9	3.87	(Swapna <i>et al.</i> , 2015)
PKAPbNER10	6.91	2.06	30%	46	67.3	310	138.6	(Basavapoomima <i>et al.</i> , 2017)
OCBTER0.1	9.86	6.56	66%	29.6	48.65	144	291.88	(Sailaja <i>et al.</i> , 2021)

Er³⁺-doped glass systems (Sosa *et al.*, 2005; Azlan *et al.*, 2019; Beltaif *et al.*, 2019; Ennouri *et al.*, 2019; Khan *et al.*, 2020; Mariyappan *et al.*, 2020). The comparison reveals that the ligand field experienced by Er³⁺ ions in the present glass host demonstrates higher local symmetry and bonding efficiency than those observed in several previously reported phosphate and tellurite-based systems. Radiative parameters such as stimulated emission cross-section (σ), spontaneous transition probability (A), branching ratio (β_R), and both calculated (τ_{cal}) and experimental (τ_{exp}) lifetimes are key indicators of the laser performance of luminescent materials. These properties were calculated for the present glasses using the previously determined Judd-Ofelt parameters and standard equations from the literature (Mariyappan *et al.*, 2017).

The branching ratio (β_R) is a critical factor for assessing the radiative efficiency of specific transitions. For effective laser action, β_R should ideally exceed 0.5. In the current study, the ⁴I_{13/2} → ⁴I_{15/2} transition in Er³⁺-doped glasses exhibited β_R values above this threshold, indicating its suitability for stimulated emission.

The stimulated emission cross-section (σ) is a predominant parameter that determines

the potential of a material for continuous-wave (CW) laser operation and optical amplification.

The σ value for the ⁴I_{13/2} → ⁴I_{15/2} transition in the 1.5 mol% Er³⁺ sample was calculated to be $33.68 \times 10^{-22} \text{ cm}^2$, indicating a high potential for low-threshold, high-gain laser applications (Yousef *et al.*, 2015; Basavapoomima *et al.*, 2017).

This near-infrared (NIR) emission transition falls within the broad spectral range of 1,460-1,625 nm, which includes the S-band (1,460-1,530 nm), C-band (1,530-1,565 nm), and L-band (1,565-1,625 nm). These regions are of high relevance for both upconversion lasers and fiber-optic amplifiers (Kaur *et al.*, 2019).

Further analysis involved evaluating gain bandwidth ($\sigma \times \Delta\lambda_{eff}$) and optical gain ($\sigma \times \tau_{cal}$), which are essential for assessing amplifier performance. The computed results are presented in Table 4. A comparative analysis with other Er³⁺-doped glass hosts is shown in Table 5, revealing that the present σ value is higher than that reported by Swapna *et al.* (2015) and Sailaja *et al.* (2021), but slightly lower than those in Basavapoomima *et al.*, (2017) and Mariyappan *et al.* (2020).

Overall, the large emission cross-section, broad bandwidth, and strong radiative parameters

make the 1.5 mol% Er^{3+} -doped phospho-tellurite glass a promising candidate for the development of eye-safe NIR lasers and optical amplifiers operating around 1.53 μm .

McCumber

McCumber theory is essential in rare-earth-doped laser glass research because it enables the quantitative evaluation of net optical gain, which Judd-Ofelt analysis alone cannot provide. While JO theory calculates intrinsic radiative properties such as spontaneous emission probability, stimulated emission cross-section, and radiative lifetime, it assumes ideal conditions and does not account for spectral overlap between absorption and emission bands or reabsorption effects within the gain medium.

In contrast, McCumber theory provides a thermodynamically consistent relationship between the absorption (σ_a) and emission (σ_e) cross-sections based on experimental spectra and temperature-dependent population distributions. These parameters are essential for assessing the potential laser performance of the $^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transition of Er^{3+} ions, particularly within the near-infrared (NIR) region relevant to telecommunications. The σ_a and σ_e values were calculated over the spectral range of 1,400-1,700 nm using McCumber's relation as reported in the literature (Azlan *et al.*, 2019). This framework allows not only the calculation of more realistic σ_e values but also the determination of net gain as a function of population inversion ratio (γ) a critical factor for practical laser design.

For the 1.5 mol% Er^{3+} -doped phospho-tellurite glass, the measured σ_a and σ_e values were found to be $0.64 \times 10^{-22} \text{ cm}^2$ and $0.85 \times 10^{-22} \text{ cm}^2$, respectively. These values, illustrated in Figure 7, indicate strong NIR absorption and efficient stimulated emission in the C-band.

In general, due to the spectral overlap between absorption and emission bands around 1,536 nm, the stimulated emission cross-section (σ_e) obtained using Judd-Ofelt theory tends to be higher than that derived via McCumber theory. This is attributed to the reabsorption effects within the gain medium, which are inherently accounted for in the Mc-Cumber model (Mariyappan *et al.*, 2020).

Using the σ_a and σ_e data, the gain coefficient ($g(\lambda)$) was calculated as a function of wavelength and population inversion ratio (γ), following standard expressions in the literature (Yousef *et al.*, 2015). As shown in Figure 8, positive gain is achieved when γ exceeds 0.6. This indicates that a population inversion of at least 60% is required to attain net amplification in the C-band (1,530-

1,564 nm), a spectral window critical for optical communication systems.

The broad and flat gain profile observed supports the conclusion that the 1.5 mol% erbium-doped phospho-tellurite glass is a highly suitable candidate for 1,536 nm laser operation and amplification in fiber-optic telecommunication applications.

Conclusions

Er^{3+} -doped phospho-tellurite glasses were successfully synthesized and characterized for their structural and optical properties. The XRD and FTIR analyses confirmed the amorphous nature and formation of a mixed glass network. Optical absorption and emission studies revealed strong NIR luminescence at 1.53 μm , suitable for optical amplifiers.

Judd-Ofelt analysis showed that the glasses possess favorable asymmetry and rigidity, with high Ω_2 values indicating strong radiative transitions. Radiative parameters including a high stimulated emission cross-section ($33.68 \times 10^{-22} \text{ cm}^2$), branching ratio (>0.5), and broad emission bandwidth support their potential for laser action and amplification.

McCumber analysis further confirmed positive gain in the C-band region for population inversion levels above 60%, highlighting their applicability in fiber-optic communication.

Overall, the 1.5 mol% Er^{3+} -doped phospho-tellurite glass exhibits excellent luminescent and gain properties, making it a promising material for use in eye-safe NIR lasers and optical amplifiers operating at 1.53 μm .

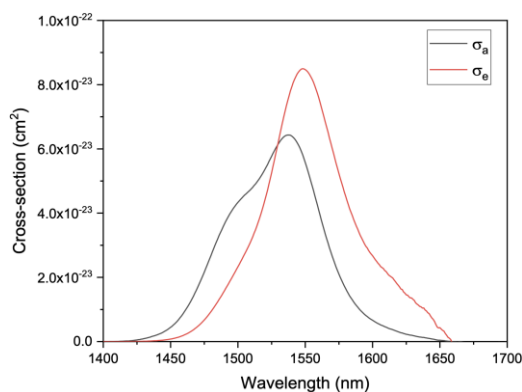


Figure 7. Absorption and emission cross-section for the $^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transition of the 1.5 mol% of erbium-doped phospho-tellurite glass

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