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Spectroscopic Properties of Er³⁺ Doped in Zinc Lithium Calcium Potassiumniobate Phosphate Glasses

Pankaj Deedwaniya¹, S. L. Meena²

^{1,2}Ceramic Laboratory, Department of physics, Jai Narain Vyas University, Jodhpur 342001(Raj) India

Abstract: Zinc lithium calcium potassiumniobate phosphate glasses containing Er³⁺ in (45-x): P₂O₅:10ZnO:10Li₂O:10CaO:10K₂O:15Nb₂O₅:xEr₂O₃, (where x=1, 1.5,2 mol %) have been prepared by melt-quenching method. The amorphous nature of the glasses was confirmed by x-ray diffraction studies. Optical absorption, Excitation, and fluorescence spectra were recorded at room temperature for all glass samples. Judd-Ofelt intensity parameters Ω_{λ} ($\lambda=2, 4, 6$) are evaluated from the intensities of various absorption bands of optical absorption spectra. Using these intensity parameters various radiative properties like spontaneous emission probability, branching ratio, radiative life time and stimulated emission cross-section of various emission lines have been evaluated.

Keywords: ZLCPNP Glasses, Optical Properties, Judd-Ofelt Theory.

I. INTRODUCTION

Rare-earth ions doped glass-ceramics are important materials for optical fibers, wave guide lasers, sensors and optical amplifiers [1-5].Oxide glasses are the most stable host matrices for practical applications due to their high chemical durability and thermal stability[6-10].Phosphate glasses are extremely attractive materials for linear and non-linear application in optics, due to their important aspects such as their low melting temperature, low phonon energy, high refractive index, high dielectric constant, good chemical durability, high thermal stability, good solubility of rare earth ions[11-16].The addition of heavy metal oxide to phosphate glasses decreases the phonon energy. Thus, leads to increase in its quantum efficiency of luminescence from the excited state of rare earth ions .Er³⁺ doped rare earth doped glasses considerable literature has recently emerged concerning the structure, optical, mechanical, thermal, and electrical properties [17-20].

In this work, the spectroscopic properties of Er³⁺-doped (45-x): P₂O₅:10ZnO:10Li₂O:10CaO:10K₂O:15Nb₂O₅:xEr₂O₃ (where x=1, 1.5,2 mol %) glasses were investigated. The Optical absorption, Excitation and fluorescence spectra of Er³⁺ of the glasses were investigated. The intensities of the transitions for the rare earth ions have been estimated successfully using the Judd-Ofelt theory, The laser parameters such as radiative probabilities(A),branching ratio (β), radiative life time(τ_R) and stimulated emission cross section(σ_p) are evaluated using J.O.intensity parameters(Ω_{λ} , $\lambda=2,4$ and 6).

II. EXPERIMENTAL TECHNIQUES

A. Preparation of Glasses

The following Er³⁺ doped zinc lithium calcium potassiumniobate phosphate glass samples (45-x): P₂O₅:10ZnO:10Li₂O:10CaO:10K₂O:15Nb₂O₅:xEr₂O₃ (where x=1, 1.5,2) have been prepared by melt-quenching method. Analytical reagent grade chemical used in the present study consist of P₂O₅, ZnO, Li₂O, CaO, K₂O, Nb₂O₅ and Er₂O₃. All weighed chemicals were powdered by using an Agate pestle mortar and mixed thoroughly before each batch (10g) was melted in alumina crucibles in silicon carbide based an electrical furnace.

Silicon Carbide Muffle furnace was heated to working temperature of 1070⁰C, for preparation of zinc lithium calcium potassiumniobate phosphate glasses, for two hours to ensure the melt to be free from gases. The melt was stirred several times to ensure homogeneity. For quenching, the melt was quickly poured on the steel plate & was immediately inserted in the muffle furnace for annealing. The steel plate was preheated to100⁰C.While pouring; the temperature of crucible was also maintained to prevent crystallization. And annealed at temperature of 350⁰C for 2h to remove thermal strains and stresses. Every time fine powder of cerium oxide was used for polishing the samples. The glass samples so prepared were of good optical quality and were transparent. The chemical compositions of the glasses with the name of samples are summarized in Table 1

Table 1 Chemical composition of the glasses

Sample	Glass composition (mol %)
ZLCPNP (UD)	45 P ₂ O ₅ :10ZnO:10Li ₂ O:10CaO:10K ₂ O:15Nb ₂ O ₅
ZLCPNP (ER 1)	44 P ₂ O ₅ :10ZnO:10Li ₂ O:10CaO:10K ₂ O:15Nb ₂ O ₅ :1 Er ₂ O ₃
ZLCPNP (ER 1.5)	43.5 P ₂ O ₅ :10ZnO:10Li ₂ O:10CaO:10K ₂ O:15Nb ₂ O ₅ :1.5 Er ₂ O ₃
ZLCPNP (ER 2)	43 P ₂ O ₅ :10ZnO:10Li ₂ O:10CaO:10K ₂ O:15Nb ₂ O ₅ : 2 Er ₂ O ₃

ZLCPNP (UD)—Represents undoped Zinc Lithium Calcium Potassiumniobate phosphate glass specimen.
ZLCPNP (ER) -Represents Er³⁺ doped Zinc Lithium Calcium Potassiumniobate phosphate glass specimens.

III. THEORY

A. Oscillator Strength

The intensity of spectral lines are expressed in terms of oscillator strengths using the relation [21].

$$f_{\text{expt.}} = 4.318 \times 10^{-9} [\epsilon(v) d v] \quad (1)$$

where, $\epsilon(v)$ is molar absorption coefficient at a given energy v (cm⁻¹), to be evaluated from Beer–Lambert law.

Under Gaussian Approximation, using Beer–Lambert law, the observed oscillator strengths of the absorption bands have been experimentally calculated, using the modified relation [22].

$$P_m = 4.6 \times 10^{-9} \times \frac{1}{cl} \log \frac{I_0}{I} \times \Delta v_{1/2} \quad (2)$$

where c is the molar concentration of the absorbing ion per unit volume, l is the optical path length, $\log I_0/I$ is absorbivity or optical density and $\Delta v_{1/2}$ is half band width.

B. Judd-Ofelt Intensity Parameters

According to Judd [23] and Ofelt [24] theory, independently derived expression for the oscillator strength of the induced forced electric dipole transitions between an initial J manifold $|4f^N(S, L) J\rangle$ level and the terminal J' manifold $|4f^N(S', L') J'\rangle$ is given by:

$$\frac{8\pi^2 mc \bar{\nu}}{3h(2J+1)n} \frac{1}{n} \left[\frac{(n^2+2)^2}{9} \right] \times S(J, J') \quad \text{where,} \quad (3)$$

the line strength $S(J, J')$ is given by the equation

$$S(J, J') = e^2 \sum_{\lambda=2, 4, 6} \Omega_{\lambda} \langle 4f^N(S, L) J || U^{(\lambda)} || 4f^N(S', L') J' \rangle^2 \quad (4)$$

In the above equation m is the mass of an electron, c is the velocity of light, $\bar{\nu}$ is the wave number of the transition, h is Planck's constant, n is the refractive index, J and J' are the total angular momentum of the initial and final level respectively, Ω_{λ} ($\lambda = 2, 4$ and 6) are known as Judd-Ofelt intensity parameters.

C. Radiative Properties

The Ω_{λ} parameters obtained using the absorption spectral results have been used to predict radiative properties such as spontaneous emission probability (A) and radiative life time (τ_R), and laser parameters like fluorescence branching ratio (β_R) and stimulated emission cross section (σ_p).

The spontaneous emission probability from initial manifold $|4f^N(S', L') J'\rangle$ to a final manifold $|4f^N(S, L) J\rangle$ is given by:

$$A[(S', L') J'; (S, L) J] = \frac{64 \pi^2 \bar{\nu}^3}{3h(2J'+1)} \left[\frac{n(n^2+2)^2}{9} \right] \times S(J', J) \quad (5)$$

Where, $S(J, J') = e^2 [\Omega_2 || U^{(2)} ||^2 + \Omega_4 || U^{(4)} ||^2 + \Omega_6 || U^{(6)} ||^2]$

The fluorescence branching ratio for the transitions originating from a specific initial manifold $|4f^N(S', L') J'\rangle$ to a final manifold $|4f^N(S, L) J\rangle$ is given by

$$\beta[(S', L') J'; (S, L) J] = \sum_{S L J} \frac{A[(S' L) J']}{A[(S' L') J' (S L) J]} \quad (6)$$

where, the sum is over all terminal manifolds.

The radiative life time is given by

$$\tau_{rad} = \sum_{S, L, J} A[(S', L') J'; (S, L) J] = A_{Total}^{-1} \quad (7)$$

where, the sum is over all possible terminal manifolds. The stimulated emission cross-section for a transition from an initial manifold $|4f^N(S', L') J\rangle$ to a final manifold $|4f^N(S, L) J\rangle$ is expressed as

$$\sigma_p(\lambda_p) = \left[\frac{\lambda_p^4}{8\pi c n^2 \Delta\lambda_{eff}} \right] \times A[(S', L') J'; (\bar{S}, \bar{L}) \bar{J}] \quad (8)$$

where, λ_p the peak fluorescence wavelength of the emission band and $\Delta\lambda_{eff}$ is the effective fluorescence line width.

D. Nephelauxetic Ratio (β') and Bonding Parameter ($b^{1/2}$)

The nature of the R-O bond is known by the Nephelauxetic Ratio (β') and Bonding Parameters ($b^{1/2}$), which are computed by using following formulae [25, 26]. The Nephelauxetic Ratio is given by

$$\beta' = \frac{v_g}{v_a} \quad (9)$$

where, v_a and v_g refer to the energies of the corresponding transition in the glass and free ion, respectively. The value of bonding parameter ($b^{1/2}$) is given by

$$b^{1/2} = \left[\frac{1 - \beta'}{2} \right]^{1/2} \quad (10)$$

IV. RESULT AND DISCUSSION

A. XRD Measurement

Figure 1 presents the XRD pattern of the samples containing show no sharp Bragg's peak, but only a broad diffuse hump around low angle region. This is the clear indication of amorphous nature with in the resolution limit of XRD instrument.

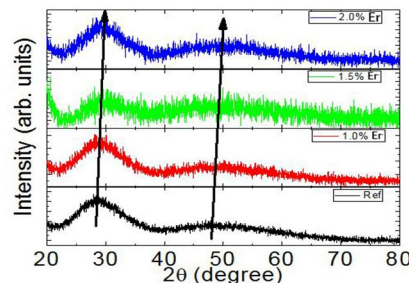


Fig.1: X-ray diffraction pattern of ZLCPNP (ER) glasses.

B. Absorption Spectra

The absorption spectra of ZLCPNP ER(01) glass, consists of absorption bands corresponding to the absorptions from the ground state $^4I_{15/2}$ of Er^{3+} ions. Ten absorption bands have been observed from the ground state $^4I_{15/2}$ to excited states $^4I_{11/2}$, $^4I_{9/2}$, $^4F_{9/2}$, $^4S_{3/2}$, $^2H_{11/2}$, $^4F_{7/2}$, $^4F_{5/2}$, $^4F_{3/2}$, $^2H_{9/2}$ and $^4G_{11/2}$ for Er^{3+} doped ZLCPNP ER (01) glass.

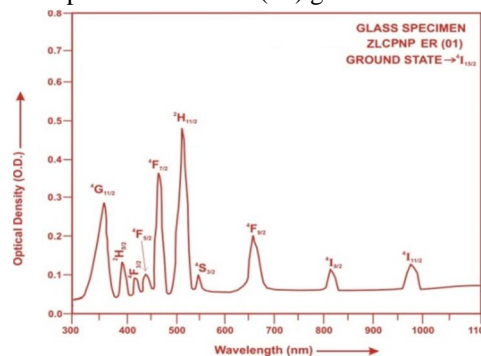


Fig.2: Absorption spectra of ZLCPNP ER (01) glass.

The experimental and calculated oscillator strengths for Er³⁺ ions in zinc lithium calcium potassium niobate phosphate glasses are given in Table 2

Table 2. Measured and calculated oscillator strength (P^m × 10⁺⁶) of Er³⁺ ions in ZLCPNP glasses.

Energy level ⁴ I _{15/2}	Glass ZLCPNP (ER01)		Glass ZLCPNP (ER1.5)		Glass ZLCPNP (ER02)	
	P _{exp.}	P _{cal.}	P _{exp.}	P _{cal.}	P _{exp.}	P _{cal.}
⁴ I _{11/2}	0.88	0.68	0.86	0.69	0.83	0.68
⁴ I _{9/2}	0.48	0.16	0.45	0.15	0.43	0.15
⁴ F _{9/2}	2.48	1.52	2.42	1.49	2.40	1.49
⁴ S _{3/2}	0.35	0.62	0.33	0.62	0.31	0.62
² H _{11/2}	6.45	2.36	6.42	2.37	6.39	2.37
⁴ F _{7/2}	5.36	2.17	5.33	2.17	5.30	2.16
⁴ F _{5/2}	0.62	0.79	0.64	0.79	0.62	0.79
⁴ F _{3/2}	0.30	0.48	0.27	0.49	0.25	0.48
² H _{9/2}	1.65	0.93	1.62	0.93	1.59	0.93
⁴ G _{11/2}	4.85	6.79	4.82	6.80	4.78	6.79
R.m.s.deviation	1.7993		1.7862		1.7778	

The various energy interaction parameters like Slater-Condon parameters F_k (k=2, 4, 6), Lande' parameter (ξ_{4f}) and Racah parameters E^k (k=1, 2, 3) have been computed using partial regression. Computed values of Slater-Condon, Lande', Racah, nephelauxetic ratio and bonding parameter for Er³⁺ doped ZLCPNP glass specimens are given in Table 3.

Table3. Computed values of Slater-Condon, Lande', Racah, nephelauxetic ratio and bonding parameter for Er³⁺ doped ZLCPNP glass specimens.

Parameter	Free ion	ZLCPNP ER01	ZLCPNP ER1.5	ZLCPNP ER02
F ₂ (cm ⁻¹)	441.680	433.883	433.874	433.894
F ₄ (cm ⁻¹)	68.327	67.048	67.0604	67.0363
F ₆ (cm ⁻¹)	7.490	7.0395	7.0401	7.0408
ξ _{4f} (cm ⁻¹)	2369.400	2414.822	2414.745	2415.158
E ¹ (cm ⁻¹)	6855.300	6661.445	6661.832	6661.517
E ² (cm ⁻¹)	32.126	31.335	31.3304	31.3411
E ³ (cm ⁻¹)	645.570	643.699	643.694	643.657
F ₄ /F ₂	0.15470	0.15453	0.15456	0.154499
F ₆ /F ₂	0.01696	0.016225	0.016226	0.0162271
E ¹ /E ³	10.61899	10.34869	10.34937	10.34948
E ² /E ³	0.049764	0.048680	0.048673	0.0486923
β'			.99567274	.99579898
b ^{1/2}			0.046514838	0.045831333

Judd-Ofelt intensity parameters Ω_λ (λ = 2, 4 and 6) were calculated by using the fitting approximation of the experimental oscillator strengths to the calculated oscillator strengths with respect to their electric dipole contributions. In the present case the three Ω_λ parameters follow the trend Ω₄ < Ω₂ < Ω₆.

The values of Judd-Ofelt intensity parameters are given in Table 4.

Table 4. Judd-Ofelt intensity parameters for Er³⁺ doped ZLCPNP glass specimens.

Glass Specimen	Ω ₂ (pm ²)	Ω ₄ (pm ²)	Ω ₆ (pm ²)	Ω ₄ /Ω ₆
ZLCPNP (ER01)	0.7970	0.3380	0.9525	0.3549
ZLCPNP (ER1.5)	0.8171	0.3102	0.9580	0.3238
ZLCPNP (ER02)	0.8134	0.3142	0.9516	0.3302

C. Excitation Spectrum

The Excitation spectra of Er³⁺ doped ZLCPNP glass specimens have been presented in Figure 3 in terms of Excitation Intensity versus wavelength. The excitation spectrum was recorded in the spectral region 300–600 nm fluorescence at 550nm having different excitation band centered at 350,365, 381, 425, 450, 470and 515 nm are attributed to the ²K_{15/2}, ⁴G_{9/2}, ⁴G_{11/2}, ²G_{9/2}, ⁴F_{3/2}, ⁴F_{5/2} and ²H_{11/2} transitions, respectively. The highest absorption level is ⁴G_{11/2} and is at 381nm. So this is to be chosen for excitation wavelength

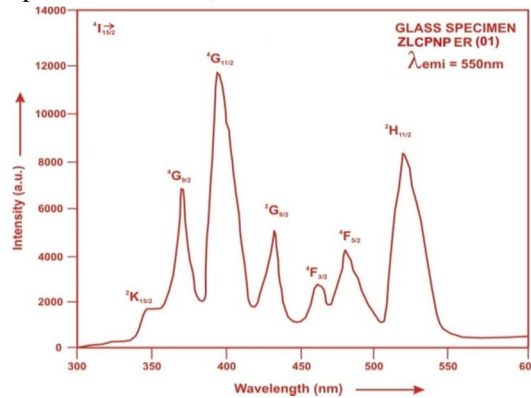


Fig.3: Excitation Spectrum of ZLCPNP ER (01) glass.

D. Fluorescence Spectrum

The fluorescence spectrum of Er³⁺ doped in zinc lithium calcium potassiumniobate phosphate glass is shown in Figure 4. There are four broad bands (⁴F_{7/2}→⁴I_{15/2}), (²H_{11/2}→⁴I_{15/2}), (⁴S_{3/2}→⁴I_{15/2}) and (⁴F_{9/2}→⁴I_{15/2}), respectively for glass specimens.

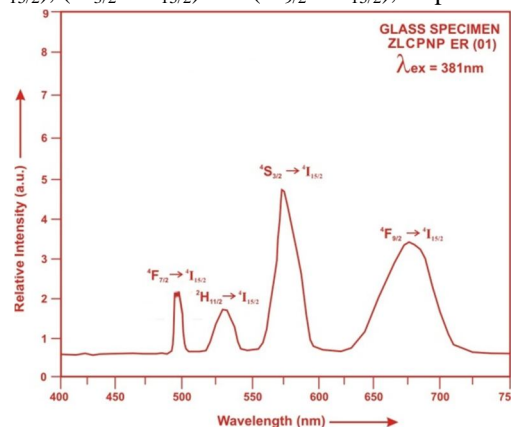


Fig.4: Fluorescence spectrum of ZLCPNP ER (01) glass.

Table 5. Emission peak wave lengths (λ_p), radiative transition probability (A_{rad}), branching ratio (β_R), stimulated emission crosssection (σ_p), and radiative life time (τ) for various transitions in Er³⁺ doped ZLCPNP glasses.

Transition	ZLCPNP ER 01					ZLCPNP ER 1.5					ZLCPNP ER 02			
	λ_{max} (nm)	$A_{rad}(s^{-1})$	β	$\sigma_p(10^{-20} cm^2)$	$\tau_R(\mu s)$	$A_{rad}(s^{-1})$	β	$\sigma_p(10^{-20} cm^2)$	$\tau_R(\mu s)$	$A_{rad}(s^{-1})$	β	$\sigma_p(10^{-20} cm^2)$	$\tau_R(10^{-20} cm^2)$	
⁴ F _{7/2} → ⁴ I _{15/2}	485	2090.68	0.4295	0.5212	205.4	2090.2	0.4275	0.5071	204.5	2085.42	0.4273	0.4918	204.91	
² H _{11/2} → ⁴ I _{15/2}	530	1223.23	0.2513	0.3639		1249.0	0.2555	0.3604		1248.80	0.2559	0.3521		
⁴ S _{3/2} → ⁴ I _{15/2}	550	918.19	0.1886	0.2639		925.35	0.1893	0.2557		920.89	0.1887	0.2482		
⁴ F _{9/2} → ⁴ I _{15/2}	657	635.95	0.1306	0.3212		624.34	0.1277	0.3081		625.19	0.1281	0.3031		

V. CONCLUSION

In the present study, the glass samples of composition (45-x): $P_2O_5:10ZnO:10Li_2O:10CaO:10K_2O:15Nb_2O_5:xEr_2O_3$ (where $x = 1, 1.5, 2$ mol %) have been prepared by melt-quenching method. The value of stimulated emission cross-section (σ_p) is found to be maximum for the transition ($^4F_{7/2} \rightarrow ^4I_{15/2}$) for glass ZLCPNP (ER 01), suggesting that glass ZLCPNP (ER 01) is better compared to the other two glass systems ZLCPNP (ER1.5) and ZLCPNP (ER02).

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