

Spectral, Transmittance and Thermal Analysis of Tb³⁺ doped Ytterbium Zinc Lithium Calcium Borogermanate Glasses

S.L.Meena

Ceremic Laboratory, Department of physics, Jai Narain Vyas University, Jodhpur 342001(Raj.) India

Abstract

Glass sample of Yttrium Zinc Lithium Sodalime Cadmium Borogermanate Glasses (25-x) GeO₂:10ZnO:10Li₂O:10Na₂O:10CaO:10CdO:10Y₂O₃:15B₂O₃:xTb₂O₃ (where x=1,1.5,2 mol%) have been prepared by melt-quenching technique. The amorphous nature of the prepared glass samples was confirmed by X-ray diffraction. DTA curve was analysed to evaluate the glass transition temperature, crystallization temperature and melting temperature. The absorption and fluorescence spectra of three Tb³⁺ doped yttrium zinc lithium sodalime cadmium borogermanate glasses have been recorded at room temperature. The various interaction parameters like Slater-Condon parameter F_2 , Lande' parameter (ζ_{4f}), nephelauxetic ratio (β') and bonding parameter ($b^{1/2}$) have been computed. Judd-Ofelt intensity parameters and laser parameters have also been calculated.

Keywords: YZSLCBG glasses, Thermal Properties, Optical properties, Transmittance analysis.

I. Introduction

Rare earth doped glasses have attracted much attention, because they have potential applications such as optical amplifiers, waveguide laser, optoelectronic devices, optical waveguide and solid state ionic devices [1-5]. Among many other glasses the germanate glasses find wide spread applications in laser technologies, optical data transmission, laser action and thermionic emission. Germanate glasses doped with rare-earth ions are considered as valuable materials for physical, optical and electrical applications. The high density in germanate glasses is due to high solubility of rare earth ions in germanate network. Glasses contain B₂O₃ have received increased attention due to their application in the field of glass ceramics, thermal sensors, reflecting windows, [6-10]. The addition zinc oxide improves the glass forming ability and to ensure low rates of crystallization in the glass system. Lithium oxide is added in the glass matrix to increase thermal stability and chemical durability of the glasses. Among active rare earth ions Tb³⁺ exhibits high solubility in ceramic glasses, which also possess excellent physical, optical, thermal and luminescent properties [11-15]. Recently germanate based glasses have a wide range of potential applications in laser technology, optical data transmission, sensing, energy solar cell and NIR lasers applications [16-18].

The aim of the present study is to prepare the Tb³⁺ doped yttrium zinc lithium sodalime cadmium borogermanate glass with different Tb₂O₃ concentrations. The absorption, fluorescence and transmittance spectra of Tb³⁺ of the glasses were investigated. The Judd-Ofelt theory has been applied to compute the intensity parameters Ω_λ ($\lambda=2, 4, 6$). These intensity parameter have been used to evaluate optical properties such as spontaneous emission probability, branching ratio, radiative life time and stimulated emission cross section. DTA curve was analysed to evaluate the glass transition temperature, crystallization temperature and melting temperature.

II. Experimental Techniques

Preparation of glasses

The following Tb³⁺ doped borogermanate glass samples (25-x) GeO₂:10ZnO:10Li₂O:10Na₂O:10CaO:10CdO:10Y₂O₃:15B₂O₃:xTb₂O₃ (where x=1,1.5, 2) have been prepared by melt-quenching method. Analytical reagent grade chemical used in the present study consist of GeO₂, ZnO, Li₂O, Na₂O, CaO, CdO, Yb₂O₃, B₂O₃ and Tb₂O₃. They were thoroughly mixed by using an agate pestle mortar. then melted at 980°C by an electrical muffle furnace for 2h., After complete melting, the melts were quickly poured in to a preheated stainless steel mould and annealed at temperature of 250°C 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 %)
YZLSLCBG (UD)	25 GeO ₂ :10ZnO:10Li ₂ O:10Na ₂ O:10CaO:10CdO:10Y ₂ O ₃ :15B ₂ O ₃
YZLSLCBG TB (1.0)	24 GeO ₂ :10ZnO:10Li ₂ O:10Na ₂ O:10CaO:10CdO:10Y ₂ O ₃ :15B ₂ O ₃ : 1 Tb ₂ O ₃
YZLSLCBG TB (1.5)	23.5 GeO ₂ :10ZnO:10Li ₂ O:10Na ₂ O:10CaO:10CdO:10Y ₂ O ₃ :15B ₂ O ₃ : 1.5 Tb ₂ O ₃
YZLSLCBG TB (2.0)	23 GeO ₂ :10ZnO:10Li ₂ O:10Na ₂ O:10CaO:10CdO:10Y ₂ O ₃ :15B ₂ O ₃ : 2 Tb ₂ O ₃
YZLSLCBG (UD)	-Represents undoped Yttrium Zinc Lithium Sodalime cadmium Borogerminate glass specimen.
YZLSLCBG (TB)	-Represents Tb ³⁺ doped Yttrium Zinc Lithium Sodalime cadmium Borogerminate glass specimens.

III. Theory**3.1 Oscillator Strength**

The spectral intensity is expressed in terms of oscillator strengths using the relation [19].

$$f_{\text{expt.}} = 4.318 \times 10^{-9} \int \varepsilon(\nu) d\nu \quad (1)$$

Where, $\varepsilon(\nu)$ is molar absorption coefficient at a given energy ν (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 [20], using the modified relation:

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

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

3.2. Judd-Ofelt Intensity Parameters

According to Judd [21] and Ofelt [22] 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:

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

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

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

In the above equation m is the mass of an electron, c is the velocity of light, ν 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} ($\lambda = 2, 4, 6$) are known as Judd-Ofelt intensity parameters.

3.3 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:

$$A[(S', L') J'; (S, L) J] = \frac{64 \pi^2 \nu^3}{3h(2J'+1)} \left[\frac{n(n^2+2)^2}{9} \right] \times S(J', \bar{J}) \quad (4)$$

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 many fold $|4f^N(S, L) J\rangle$ is given by

$$\beta[(S', L') J'; (S, L) J] = \sum_{S L J} \frac{A[(S' L)]}{A[(S' L') J'(\bar{S} L)]} \quad (5)$$

Where, the sum is over all terminal manifolds.

The radiative life time is given by

$$\tau_{rad} = \sum_{S L J} A[(S', L') J'; (S, L) J] = A_{Total}^{-1} \quad (6)$$

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

$$\sigma_p(\lambda_p) = \left[\frac{\lambda_p^4}{8\pi c n^2 \Delta\lambda_{eff}} \right] \times A[(S', L') J'; (\bar{S}, \bar{L}) J] \quad (7)$$

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

3.4 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 Parameter ($b^{1/2}$), which are computed by using following formulae [23, 24]. The Nephelauxetic Ratio is given by

$$\beta' = \frac{\nu_g}{\nu_a} \quad (8)$$

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

$$b^{1/2} = \left[\frac{1-\beta'}{2} \right]^{1/2} \quad (9)$$

IV. Result and Discussion

4.1 XRD Measurement

Figure 1 presents the XRD pattern of the sample contain – GeO₂ which is show no sharp Bragg's peak, but only a broad diffuse hump around low angle region. This is the clear indication of amorphous nature within the resolution limit of XRD instrument.

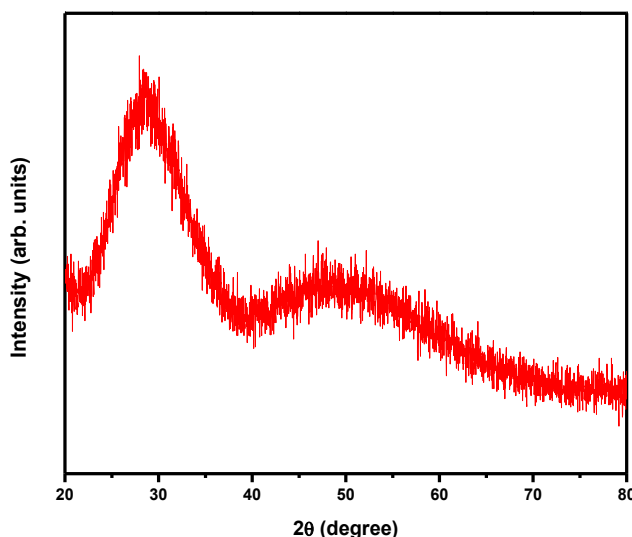


Fig.1: X-ray diffraction pattern of YZLSLCBG TB (1.0) glass.

4.2 Transmittance Spectrum

The transmittance spectrum of Tb³⁺ doped in yttrium zinc lithium sodalime cadmium borogermanate glass is shown in Figure 2.

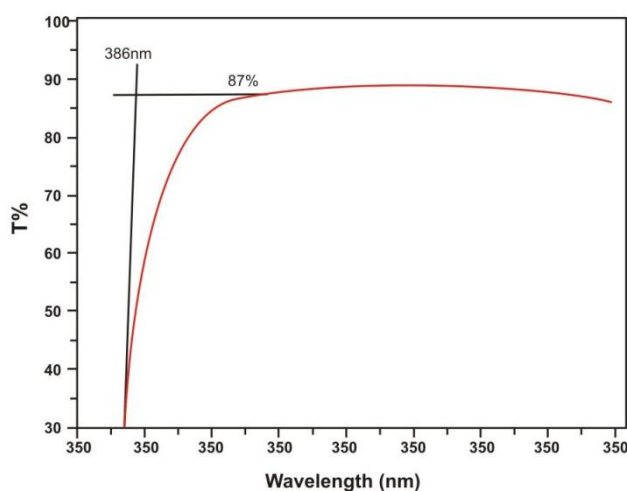


Fig.2: Transmittance spectrum of YZLSLCBG TB(1.0) glass.

4.3 Thermal Property

Differential thermal analysis checks the heat absorbed by glass samples during heating or cooling. Fig. 3 depicts the DTA thermogram of powdered YZLSLCBG sample. The glass transition temperature (T_g), onset crystallization temperature (T_c), crystallization temperature (T_p), melting temperature (T_m), thermal stability (T_s), Balaji Parameter (B_p), Hurbe's criterion (H_R) and reduced glass transition temperature (T_{rg}) were calculated. Shankar's parameter also calculated by using eq. (14). All the determined thermal parameters are given in table 2.

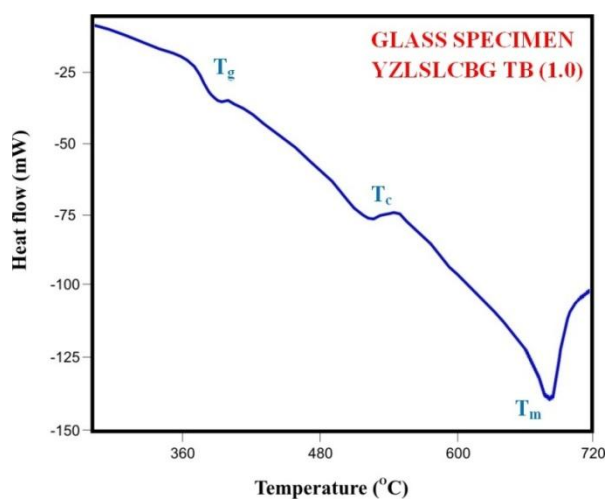


Fig.3: DTA curve of YZLSLCBG DY (1.0) glass.

Table 2. Thermal parameters determined from the DTA traces of YZLSLCBG TB glasses.

Sample Name	$T_g(^{\circ}\text{C})$	$T_c(^{\circ}\text{C})$	$T_p(^{\circ}\text{C})$	$T_m(^{\circ}\text{C})$	$T_s(^{\circ}\text{C})$	$B_p(^{\circ}\text{C})$	$H_R(^{\circ}\text{C})$	$K_S(^{\circ}\text{C})$	$T_{rg} (^{\circ}\text{C})$
YZLSLCBG TB (1.0)	376	510	548	686	134	3.526	0.216	34.379	0.548
YZLSLCBG TB (1.5)	380	511	550	688	131	3.359	0.220	33.702	0.552
YZLSLCBG TB (2.0)	386	512	555	691	126	2.930	0.240	33.640	0.559

The thermal stability of the glass samples can be calculated by difference between onset crystallization temperature and transition temperature [25].

$$\text{Thermal Stability } (T_s) = T_c - T_g \quad (10)$$

Balaji Parameter can be calculated using [25].

$$\text{Balaji Parameter } (B_p) = [(T_c - T_g)/(T_p - T_c)] \quad (11)$$

Hruby's criterion is calculated using the Hurby's relation [25].

$$\text{Hruby's criterion } (H_R) = [(T_p - T_c)/(T_m - T_c)] \quad (12)$$

Reduced glass transition temperature is given as [25].

$$\text{Reduced glass transition temperature } (T_{rg}) = T_g/T_m \quad (13)$$

Thermal Parameter is given as [25].

$$K_s = [(T_m - T_c)(T_c - T_g)/T_m] \quad (14)$$

4.4 Absorption Spectrum

The absorption spectra of Tb³⁺ doped YZLSLCBG TB (1.0) glass specimen has been presented in Figure 4 in terms of optical density versus wavelength (nm). Five absorption bands have been observed from the ground state ⁷F₆ to excited states ⁵D₄, ⁵D₃, ⁵L₁₀, ⁵D₂ and ⁵L₉ for Tb³⁺ doped YZLSLCBG TB (1.0) glass.

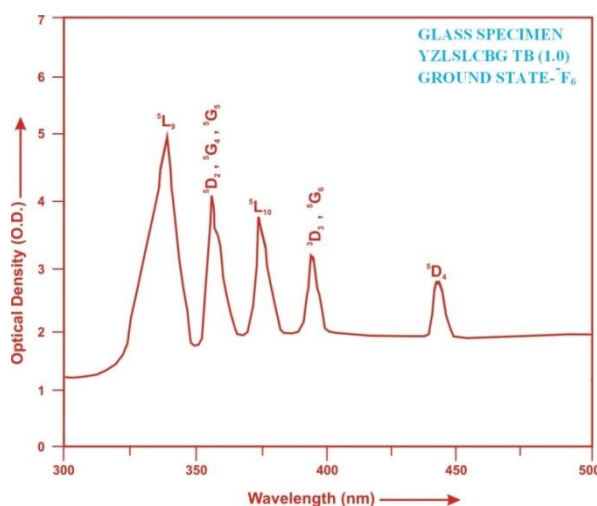


Fig.4: Absorption spectrum of YZLSLCBG TB (1.0) glass.

The experimental and calculated oscillator strengths for Tb³⁺ ions in Yttrium Zinc Lithium Sodalime cadmium Borogerminate glasses are given in Table 3.

Table3: Measured and calculated oscillator strength ($P_m \times 10^{+6}$) of Tb³⁺ ions in YZLSLCBG glasses.

Energy level ⁷ F ₀	Glass YZLSLCBG TB(1.0)		Glass YZLSLCBG TB(1.5)		Glass YZLSLCBG TB(2.0)	
	P _{exp.}	P _{cal.}	P _{exp.}	P _{cal.}	P _{exp.}	P _{cal.}
⁵ D ₄	0.57	0.06	0.55	0.06	0.53	0.07
⁵ D ₃	0.91	0.41	0.89	0.42	0.87	0.44
⁵ L ₁₀	1.61	1.16	1.58	1.16	1.56	1.18
⁵ D ₂	1.90	0.58	1.88	0.59	1.86	0.61
⁵ L ₉	2.18	1.03	2.15	1.03	2.12	1.04
r.m.s. deviation	0.8704		0.8410		0.8066	

The small value of r.m.s. deviation indicates fairness of fitting between experimental and calculated oscillator strengths.

Computed values of F₂, Lande' parameter (ξ_{4f}), Nephlauxetic ratio (β') and bonding parameter($b^{1/2}$) for Tb³⁺doped YZLSLCBG glass specimen are given in Table 4.

Table 4. F₂, ξ_{4f} , β' and $b^{1/2}$ parameters for Terbium doped glass specimen.

Glass Specimen	F ₂	ξ_{4f}	β'	$b^{1/2}$
Tb ³⁺	400.26	1820.87	0.9703	0.1219

The value of Judd-Ofelt intensity parameters are given in **Table 5**

Table5: Judd-Ofelt intensity parameters for Tb³⁺ doped YZLSLCBG glass specimens.

Glass Specimen	$\Omega_2(\text{pm}^2)$	$\Omega_4(\text{pm}^2)$	$\Omega_6(\text{pm}^2)$	Ω_4/Ω_6	Trend	References
YZLSLCBG TB(1.0)	4.688	3.031	2.675	1.133	$\Omega_2 > \Omega_4 > \Omega_6$	P.W.
YZLSLCBG TB(1.5)	5.719	3.039	2.684	1.132	$\Omega_2 > \Omega_4 > \Omega_6$	P.W.
YZLSLCBG TB(2.0)	7.420	2.797	2.723	1.027	$\Omega_2 > \Omega_4 > \Omega_6$	P.W.
PKAPN (HO)	8.680	3.040	2.370	1.283	$\Omega_2 > \Omega_4 > \Omega_6$	[26]
LLPNBP (SM)	5.152	4.553	4.198	1.085	$\Omega_2 > \Omega_4 > \Omega_6$	[27]
ZLCBP (SM)	4.599	4.096	3.813	1.074	$\Omega_2 > \Omega_4 > \Omega_6$	[28]
ZLCMBP (DY)	2.790	1.715	1.354	1.267	$\Omega_2 > \Omega_4 > \Omega_6$	[29]
	8.580	4.310	2.880	1.497	$\Omega_2 > \Omega_4 > \Omega_6$	[30]

4.5 Excitation Spectrum

Excitation spectra of YZLSLCBG TB (01) glass recorded at the emission wavelength 544 nm is depicted as figure 5. The excitation spectra was recorded in the spectral region 300-550nm fluorescence at 544 nm having different excitation band centered at 305,316,331,345,359,368,377,386 and 484 are attributed to the ⁵H₆,⁵H₇,⁵D₁,⁵L₇+⁵L₈,⁵L₉,⁵G₅,⁵L₁₀,⁵D₃+⁵G₆ and ⁵D₄ transitions respectively. The highest absorption level is ⁵D₃+⁵G₆ and is at 386 nm. So this is to be chosen for excitation wavelength.

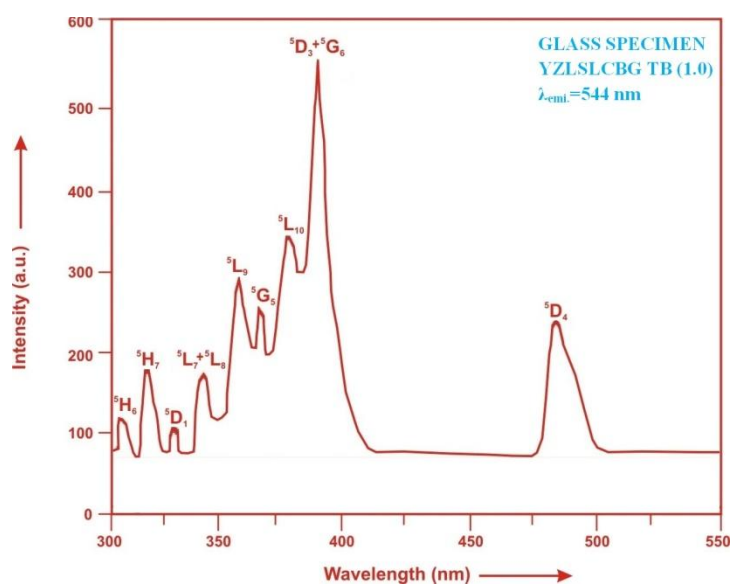


Fig.5: Excitation spectrum of YZLSLCBG TB (1.0) glass.

4.6. Fluorescence Spectrum

The fluorescence spectrum of Tb³⁺doped in Yttrium Zinc Lithium Sodalime cadmium Borogerminate glass is shown in Figure 6. There are four broad bands observed in the Fluorescence spectrum of Tb³⁺doped Yttrium Zinc Lithium Sodalime cadmium Borogerminate glass. The wavelengths of these bands along with their assignments are given in Table 5. Fig.(6).Shows the fluorescence spectrum with four peaks (⁵D₄→⁷F₆), (⁵D₄→⁷F₅), (⁵D₄→⁷F₄) and (⁵D₄→⁷F₃) for glass specimens.

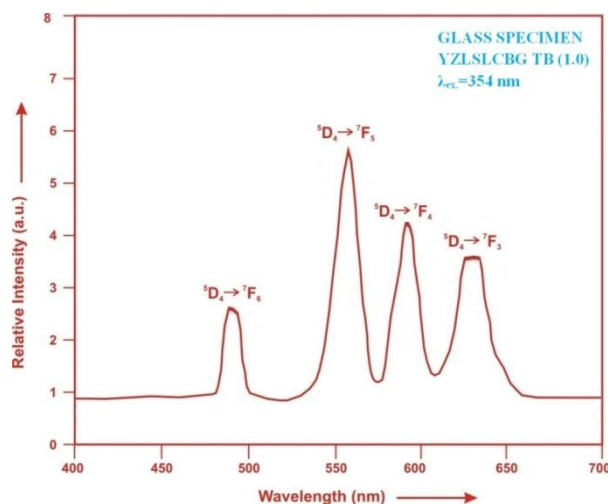


Fig.6: Fluorescence spectrum of YZLSLCBG TB (1.0) glass.

Table6. Emission peak wave lengths (λ_{\max}),radiative transition probability (A_{rad}),branching ratio (β),stimulated emission cross-section(σ_p) and radiative life time(τ_R) for various transitions in Tb³⁺doped YZLSLCBG glasses.

Transition	YZLSLCBG TB (1.0)					YZLSLCBG TB (1.5)				YZLSLCBG TB (2.0)			
	λ_{\max} (nm)	$A_{\text{rad}}(s^{-1})$	β	σ_p (10^{-20} cm^2)	$\tau_R(\mu s)$	$A_{\text{rad}}(s^{-1})$	β	σ (10^{-20} cm^2)	$\tau_R(\mu s)$	$A_{\text{rad}}(s^{-1})$	β	σ_p (10^{-20} cm^2)	$\tau_R(\mu s)$
⁵ D ₄ → ⁷ F ₆	488	2210.61	0.1122	0.347	50.75	2426.44	0.1058	0.374	43.61	2742.67	0.0978	0.413	35.66
⁵ D ₄ → ⁷ F ₅	550	12963.30	0.6579	2.253		15476.40	0.6750	2.645		19572.10	0.6979	3.303	
⁵ D ₄ → ⁷ F ₄	582	1985.88	0.1008	0.756		2042.24	0.08907	0.761		2044.33	0.0729	0.746	
⁵ D ₄ → ⁷ F ₃	625	2544.17	0.1291	0.707		2983.59	0.1301	0.819		3686.12	0.1314	0.996	

V. Conclusion

In the present study, the glass samples of composition (25-x) GeO₂: 10ZnO: 10Li₂O: 10Na₂O:10CaO:10CdO:10Y₂O₃:15B₂O₃:xTb₂O₃, (where x=1, 1.5, 2mol %) have been prepared by melt-quenching method. The Judd-Ofelt theory has been applied to calculate the oscillator strength and intensity parameters Ω_λ ($\lambda=2, 4, 6$). The radiative transition rate and the branching ratio are highest for (⁵D₄→⁷F₅) transition and hence it is useful for laser action. The stimulated emission cross section (σ_p) value is also very high for the transition (⁵D₄→⁷F₅). This shows that (⁵D₄→⁷F₅) transition is most probable transition. The large value of Balaji and Shankar parameters indicate that the prepared glass samples have good thermal stability.

References

- [1].Meena,S.L.(2025).Spectral, Thermal and Raman analysis of Ho³⁺ doped borophosphate glasses with large Balaji parameter,IOSR Appl.Phys.17,24-31.
- [2].Basavapoomima,C.H.,Masthanaiah,E.,Vijay,N.,Depuru,S.R.,Kaewkhao,J.,Pecharapa,W.,Jayasankar,C.K.(2024).Spectroscopic investigation and local structure of Eu³⁺ ions in lead phosphate glasses for optical device applications,Optik,300,171667.
- [3].Meena, S.L.(2024).Photoluminescence and Raman analysis of Nd³⁺ doped in ytterbium zinc lithium sodium barium calcium aluminophosphate glasses, IOSR Appl.Phys.16,28-34.
- [4].Hanamar,K.,Hegde,B.G.,Kolavekar,S.B.(2023).The role of Bi₂O₃ and Sm₂O₃ on the thermal properties of phosphor-zinc tellurite glasses.J.Therm.Cal.148:13263-13271.
- [5].Faznny,H.M.K.,Azlan,M.F.(2017).Optical basicity and electronic polarizability of zinc borotellurite glass doped La³⁺ ions ,Res.Phys.7,581-589.
- [6].Elan,F.,FalcaoFilho,E.L.,Camilo,M.E.Garcia,J.A.M.,Kassab,L.R.P.,Araujo,C.B.(2016).Up-conversion photoluminescence in GeO₂-PbO glass codoped with Nd³⁺ and Yb³⁺,Opt.Mater 60,313-317.
- [7].Yasukevich,A.S.,Dunia,G.,Kisel,V.E.E.,Kuleshov,N.V.(2020).Spectral luminescence properties of oxyfluoride lead silicate germinate.J.Lumin.229,117667.
- [8].Tekin,H.O.,Kassab,L.R.P.,Shams,Issa,S.A.M.,Bordon,C.D.S.,Buriah,A.Delboni,F.O.P.,Kilic,G.,Magalhaes,E.S.(2020).Structural and physical characterization study on synthesized tellurite(TeO₂) and germinate (GeO₂) glass shields using XRD,Raman spectroscopy,FLUKA and PHITS,Opt.Mater.110,110533.
- [9].Guan,P.,Fan,X.,Li,W.,Liu,X.,Yu,C.,Zhang,L.,Hu,L.(2016).High efficiency 2 μ m laser in a single-mode Tm-doped lead germinate composite fiber,Chin.Opt.Lett.14,72-75.
- [10].Zhang,Q.,Chen,G.,Zhang,G.(2009).Spectroscopic properties of Ho³⁺/Yb³⁺ codoped lanthanum aluminum germinate glasses with efficient energy transfer,J.Appl.Phys.106,113102-1131106.
- [11].Bobkoyal, N.M. and Khot,S.A.(2005). Zinc oxide in brate glass-forming systems.J.Glass and ceramics, 62,167-170.
- [12]. Pal, M., Roy, B.and Pal, M. (2011). Structural characterization of borate glasses containing zinc and manganese oxide. J.Mod.Physics, 2, 1062-66.

- [13].Meena,S.L.(2025).Spectroscopic Properties of Tm³⁺ doped in Zinc lithium alumino borophosphate glasses,IOSR Appl.Phys.12,36-41.
- [14].Dhinakaran,A.P.,Vinothkumar,P.Senthil,T.S.,Kalpana,S.(2024).Investigation on luminescence characteristics of Tb³⁺/Dy³⁺ co-doped borophosphate glass for cool white LED and radiation shielding applications,Appl.Phys.A,130.709.
- [15].Chen,Y.,Xiong,Y.,Huang,H.,Yang,B.(2021).Crystallization behavior and upconversion optical characteristics based on NaZnPO₄:Yb³⁺/Tb³⁺/Ho³⁺ nanocrystals embedded in glass matrix,J.Alloy Comp.887,161344.
- [16].Golonko,P.,Sadowska,K.,Ragin,T.,Kochanowicz,M.,Miluski,P.,Dorosz,J.,Kuwik,M.,Pisarski,W.,Pisarska,J.,Lesniak,M.(2022).Crystallization mechanism and optical properties of antimony germinate silicate glass ceramic doped with europium ions,Mat.15,3797.
- [17].Yamauchi,H.,Ohishi,Y.(2005).Spectroscopic properties of Er³⁺ doped PbO-Ga₂O₃-GeO₂ glass for optical amplifiers,Opt.Mater.27,679-690.
- [18].Zhou,D.,Jin,D.,Ni,Q.,Song,X.,Bai,X.,Han,K.(2019).Fabrication of double-cladding Ho³⁺/Tm³⁺ co-doped Bi₂O₃-GeO₂-Ga₂O₃-BaF₂ glass fiber and its performance in a 2.0 μm laser,J.Am.Ceram.Soc.102,4748-4756.
- [19].Meena,S.L.(2025).Spectral and Raman Analysis of Tb³⁺ doped Yttrium Zinc Lithium Cesium Barium Borate Glasses,IOSR Appl.Phys.17,41-47.
- [20].Meena,S.L.(2021). Spectral and Raman Analysis of Er³⁺ doped Zinc Lithium Antimony Sodalime Tellurite Glasses,Int.J.Eng.Sci.Inv.10,09-15.
- [21]. Judd, B.R. (1962). Optical Absorption Intensities of Rare Earth Ions. Physical Review, 127, 750.
- [22]. Ofelt, G.S. (1962). Intensities of Crystal Spectra of Rare Earth Ions. The J. Chem. Phys., 37, 511.
- [23].Kashif,I.Ratep,A.(2023).Luminescence in Er³⁺ co-doped bismuth germinate glass-ceramics for blue and green emitting applications,J.Korean Ceram.Soc.60,511-526.
- [24].Meena,S.L.(2021).Spectral and Raman Analysis of Sm³⁺ doped in Zinc Lithium Sodalime Alumino Silicate Glasses,Int.J.Eng.Sci.Inven.10,28-33.
- [25].Meena,S.L.(2026). Structural, Thermal and Photoluminescence analysis of Pr³⁺ doped borophosphate glasses for the visible light emitting diodes applications, IOSR Appl.Phys.18,55-62.
- [26].Rao,C.S.,Kumar,K.U.,Babu,P.,Jayasankar,C.K.(2012).Optical properties of Ho³⁺ ions in lead phosphate glasses,Opt.Mat.35,102-107.
- [27].Meena,S.L.(2021).Spectral and Raman analysis of Sm³⁺ ions doped lead lithium potassium niobate borophosphate glasses,IOSR Appl.Phys.13,32-38.
- [28]. Meena,S.L.(2021).Spectral and Raman analysis of Sm³⁺ ions doped zinc lithium cadmium borophosphate glasses, Int.J.Phys.Appl.Sci. 8,7-15.
- [29].Meena,S.L.(2022).Spectral and FTIR Analysis of Dy³⁺ ions doped zinc lithium cadmium magnesium borophosphate glasses,Int.J.Res.Appl.Sci.Eng.Tech.10,55-61.
- [30].Seshadri,M.,Ratnakaram,Y.C.,Thirupathi Naidu,D.,Rao,K.V.(2010).Investigation of spectroscopic properties(absorption and emission) of Ho³⁺ doped alkali,mixed alkali and calcium phosphate glass ,Opt.Mat.32,535-542.