IOSR Journal Of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 16, Issue 5 Ser. 1 (Sept. – Oct. 2024), PP 35-41
www.Iosrjournals.Org

Spectral and Luminescence Study of Er^{3+} Doped Phosphate Glasses for the Development of 1.5 µm Broadband Amplifier

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ABSTRACT
Ytterbium zinc lithium lead alumino antimony borophosphate glasses containing Er^{3+} in (25-x)P_2O_5: 10ZnO: 10Li_2O: 10PbO: 10Al_2O_3: 10Sb_2O_3: 10Y_2O_3: 15B_2O_3: Er_2O_3 (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 Spectrum and fluorescence spectra were recorded at room temperature for all glass samples. Judd-Ofelt intensity parameters Ω_λ (λ=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: *YZLLAABP Glasses, Optical Properties, Judd-Ofelt Theory, Rare earth ions.*

Date of Submission: 27-09-2024 Date of Acceptance: 09-10-2024

I. Introduction

Rare earth doped ceramic glasses are widely used mainly for solid state lasers, white light-emitting diodes (WLEDs), up-conversion lasers, optical amplifiers, optical communications and electro-chromic display devices [1-4].Phosphate glasses have attracted a great attention due to their several properties, such as good thermal and mechanical stabilities, low refractive index, low melting temperature, high transparency, high refractive index and high density [5-10]. Phosphate based glasses have a wide range of potential applications in optoelectronic devices, transmission, solid state lighting and laser technologies [11-13]. Glasses containing heavy metal oxides exhibits good non-linear optical properties and good chemical durability [14,15]. Boric oxide (B_2O_3) acts as a good glass former and flux material [16]. PbO is heavy metal oxide because it improves the chemical durability, thermal stability and decrease the melting temperature. Lead oxide acts as both modifier and former [17]. The low glass melting temperature .low phonon energy, good chemical durability and the optical fiber development compatibility makes the phosphate glasses suitable candidates for photonic applications [18,19]. Among different rare-earth ions, the Er^{3+}ions have been identified as the most efficient ion for obtaining the lasing action, frequency up-conversion and optical amplification [20-24].

In this work, the spectroscopic properties of Er^{3+} -doped (25-x)P_2O_5: 10ZnO: 10Li_2O: 10PbO: 10Al_2O_3: 10Sb_2O_3: 10Y_2O_3: 15B_2O_3:xEr_2O_3 (where x=1, 1.5,2 mol %) glasses were investigated for operation at the 1.55 µm wavelength. The optical absorption, excitation and fluorescence spectra of Er^{3+} 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, λ=2,4 and 6).

II. Experimental Techniques

Preparation of glasses

The following Er^{3+} doped ytterbium zinc lithium lead alumino antimony borophosphate glass samples (25-x)P_2O_5: 10ZnO: 10Li_2O: 10PbO: 10Al_2O_3: 10Sb_2O_3: 10Y_2O_3: 15B_2O_3: xEr_2O_3 (where x=1, 1.5.2) have been prepared by melt-quenching method. Analytical reagent grade chemical used in the present study consist of P_2O_5,ZnO,Li_2O,PbO,Al_2O_3,Sb_2O_3,Y_2O_3, $B_2O_3$and Er_2O_3. 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 1060^0C, for preparation of Ytterbium zinc lithium lead alumino antimony borophosphate 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 to100^{0}C.While pouring; the temperature of crucible was also maintained to prevent crystallization. And annealed at temperature of 350^{0}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 %)
YZLLAABP (UD)	$25P_2O_5$: 10ZnO: $10Li_2O$: 10PbO: $10Al_2O_3$: $10Sb_2O_3$: $10Y_2O_3$: $15B_2O_3$
YZLLAABP (ER 1)	$24P_2O_5$: 10ZnO: $10Li_2O$: 10PbO: $10Al_2O_3$: $10Sb_2O_3$: $10Y_2O_3$: $15B_2O_3$: 1 Er_2O_3
YZLLAABP (ER 1.5)	$23.5P_2O_5$: 10ZnO: $10Li_2O$: 10PbO: $10Al_2O_3$: $10Sb_2O_3$: $10Y_2O_3$: $15B_2O_3$1.5 Er_2O_3
YZLLAABP (ER 2)	$23P_2O_5$: 10ZnO: $10Li_2O$: 10PbO: $10Al_2O_3$: $10Sb_2O_3$: $10Y_2O_3$: $15B_2O_3$: 2 Er_2O_3

YZLLAABP (UD)—Represents undoped Ytterbium zinc lithium lead alumino antimony borophosphate glass specimens
YZLLAABP (ER) -Represents Er^{3+} doped Ytterbium zinc lithium lead alumino antimony borophosphate glass specimens

III. THEORY

3.1 Oscillator Strength

The intensity of spectral lines are expressed in terms of oscillator strengths using the relation [25].

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

where, ε (*ν)* 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, using the modified relation [26].

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

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

3.2. Judd-Ofelt Intensity Parameters

According to Judd [27] and Ofelt [28] 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:

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

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

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

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 (λ = 2, 4 and 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:

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

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

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

where, the sum is over all terminal manifolds.

The radiative life time is given by

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

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.

IV. Result and Discussion

4.1. 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.

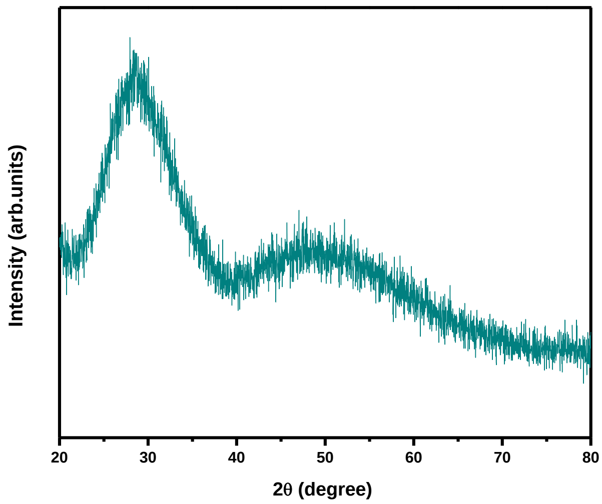

Fig.1: X-ray diffraction pattern of YZLLAABP ER (01) glass.

4.2. Absorption spectra

The absorption spectra of YZLLAABP (ER) glasses, consists of absorption bands corresponding to the absorptions from the ground state $^4I_{15/2}$ of Er^{3+} ions. Nine 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 YZLLAABP (ER) glasses.

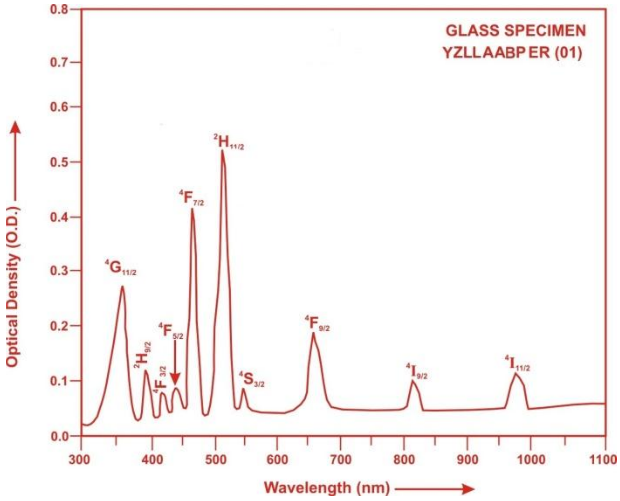

Fig.2: Vis-NIR absorption spectra of YZLLAABP ER(01) glass.

The experimental and calculated oscillator strengths for Er^{3+} ions in ytterbium zinc lithium lead alumino antimony borophosphate glasses are given in **Table 2**

Table 2. Measured and calculated oscillator strength ($P^m \times 10^{+6}$) of Er^{3+} ions in YZLLAABP glasses.

Energy level $^4I_{15/2}$	Glass YZLLAABP (ER01)		Glass YZLLAABP (ER1.5)		Glass YZLLAABP (ER02)	
	$P_{exp.}$	$P_{cal.}$	$P_{exp.}$	$P_{cal.}$	$P_{exp.}$	$P_{cal.}$
$^4I_{11/2}$	0.86	0.67	0.84	0.67	082	0.67
$^4I_{9/2}$	0.43	0.14	0.40	0.14	0.38	0.14
$^4F_{9/2}$	2.46	1.45	2.43	1.44	0.33	1.43
$^4S_{3/2}$	038	0.60	0.36	0.61	0.31	0.61
$^2H_{11/2}$	6.50	2.38	6.47	2.39	6.44	2.39
$^4F_{7/2}$	5.28	2.10	5.25	2.11	5.22	2.10
$^4F_{5/2}$	0.68	0.77	0.66	0.77	0.64	0.77
$^4F_{3/2}$	0.38	0.47	0.36	0.47	0.33	0.47
$^2H_{9/2}$	1.72	0.90	1.69	0.90	1.65	0.90
$^4G_{11/2}$	486	6.77	4.83	6.77	4.79	6.77
R.m.s.deviation	1.8044		1.7916		1.7813	

Computed values of Slater-Condon, Lande, Racah, nephelauexetic ratio and bonding parameter for Er^{3+} doped YZLLAABP glass specimens are given in **Table 3**.

Table3. Computed values of Slater-Condon, Lande′, Racah, nephelauexetic ratio and bonding parameter for Er^{3+} doped YZLLAABP glass specimens.

Parameter	Free ion	YZLLAABP ER01	YZLLAABP ER1.5	YZLLAABP ER02
$F_2(cm^{-1})$	441.680	433.93	433.99	433.98
$F_4(cm^{-1})$	68.327	67.049	67.0452	67.047
$F_6(cm^{-1})$	7.490	7.046	7.049	4.048
$\xi_{4f}(cm^{-1})$	2369.400	2414.625	2414.523	2414.537
$E^1(cm^{-1})$	6855.300	6663.203	6664.296	6664.117
$E^2(cm^{-1})$	32.126	31.345	31.356	31.353
$E^3(cm^{-1})$	645.570	643.606	643.602	643.596
F_4/F_2	0.15470	0.15451	0.15448	0.15449
F_6/F_2	0.01696	0.01624	0.016242	0.016241
E^1/E^3	10.61899	10.35292	10.35469	10.35451
E^2/E^3	0.049764	0.048702	0.0487189	0.0487156
β'		0.99580	0.99598	0.995954
$b^{1/2}$		0.04583	0.04483	0.04498

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

Table 4. Judd-Ofelt intensity parameters for Er^{3+} doped YZLLAABP glass specimens.

Glass Specimen	$\Omega_2(pm^2)$	$\Omega_4(pm^2)$	$\Omega_6(pm^2)$	Ω_4/Ω_6	Ref.
YZLLAABP (ER01)	0.8579	0.3155	0.9595	0.3288	P.W.
YZLLAABP (ER1.5)	0.8650	0.3041	0.9636	0.3156	P.W.
YZLLAABP (ER02)	0.8673	0.2994	0.9623	0.3111	P.W.
ZLMVBB (PR)	2.059	1.683	4.493	0.3746	[29]
SYB (PR)	10.57	2.94	17.85	0.1647	[30]

4.3. Excitation Spectrum

The Excitation spectra of Er^{3+}doped YZLLAABP 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.

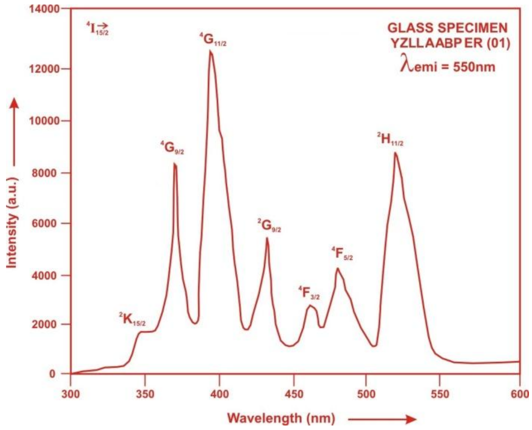

Fig.3: Excitation Spectrum of YZLLAABP ER (01) glass.

4.4. Fluorescence Spectrum

The fluorescence spectrum of Er^{3+}doped in ytterbium zinc lithium lead alumino antimony borophosphate glass is shown in Figure 4. There are seven broad bands ($^4F_{7/2}\rightarrow{}^4I_{15/2}$), ($^2H_{11/2}\rightarrow{}^4I_{15/2}$), ($^4S_{3/2}\rightarrow{}^4I_{15/2}$), ($^4F_{9/2}\rightarrow{}^4I_{15/2}$), ($^4I_{11/2}\rightarrow{}^4I_{15/2}$), ($^4I_{13/2}\rightarrow{}^4I_{15/2}$) and ($^4I_{11/2}\rightarrow{}^4I_{13/2}$) respectively for glass specimens.

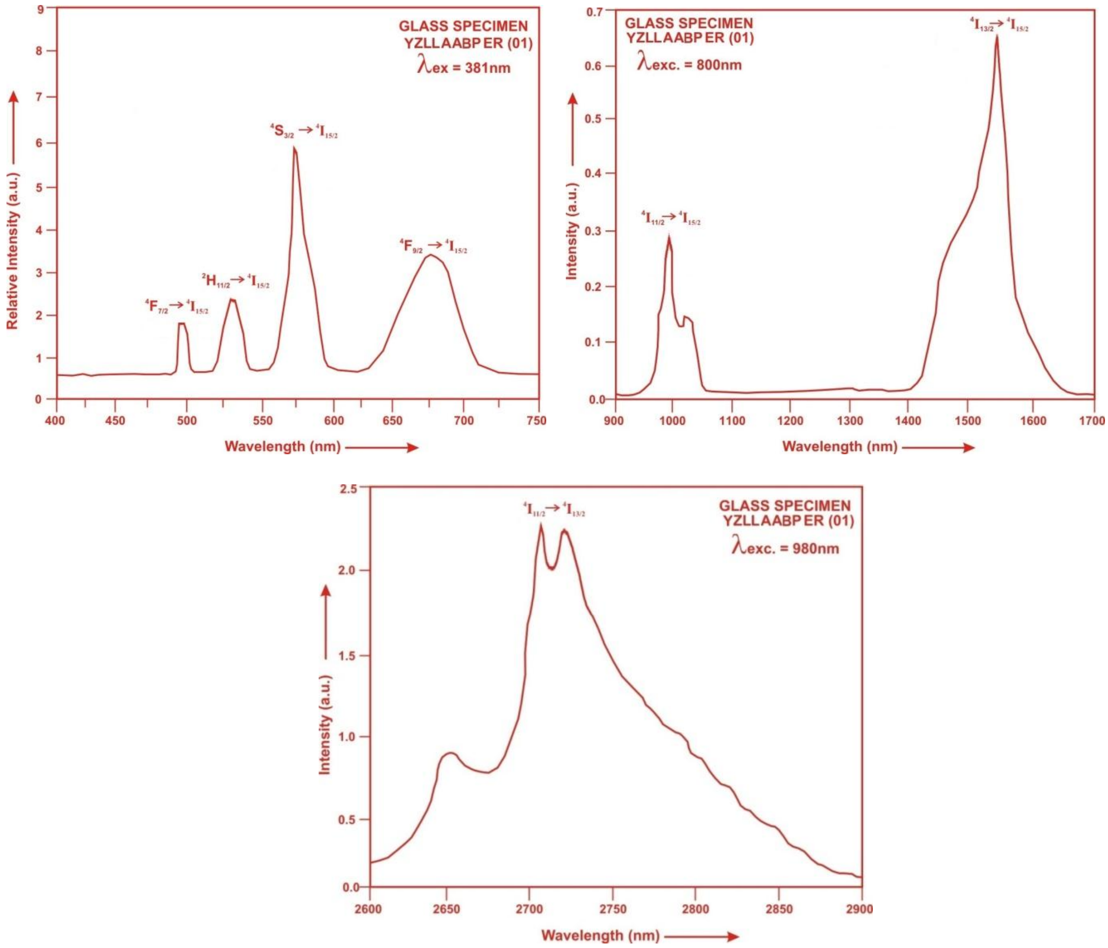

Fig.4: Excitation Spectrum of YZLLAABP ER (01) glass.

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 Er^{3+} doped YZLLAABP glasses.

Transition		YZLLAABP ER 01				YZLLAABP ER 1.5				YZLLAABP ER 02			
	λ_{max} (nm)	$A_{rad}(s^{-1})$	β	σ_p (10^{-20} cm^2)	$\tau_R(\mu s)$	$A_{rad}(s^{-1})$	β	σ_p (10^{-20} cm^2)	τ_R (μs)	$A_{rad}(s^{-1})$	β	σ_p (10^{-20} cm^2)	τ_R (10^{-20} cm^2)
$^4F_{7/2}\rightarrow^4I_{15/2}$	485	1925.20	0.4065	0.529		1931.22	0.4067	0.520		1927.98	0.4064	0.492	
$^2H_{11/2}\rightarrow^4I_{15/2}$	530	1191.51	0.2516	0.382		1195.16	0.2517	0.368		1196.37	0.2522	0.357	
$^4S_{3/2}\rightarrow^4I_{15/2}$	550	850.73	0.1796	0.259		855.53	0.1802	0.246		855.94	0.1804	0.240	
$^4F_{9/2}\rightarrow^4I_{15/2}$	657	576.93	0.1218	0.312	211.17	573.82	0.1209	0.298	210.62	571.59	0.1205	0.284	210.78
$^4I_{11/2}\rightarrow^4I_{15/2}$	990	98.31	0.0208	0.348		98.94	0.0208	0.342		98.96	0.0208	0.334	
$^4I_{13/2}\rightarrow^4I_{15/2}$	1538	79.48	0.0168	1.210		79.88	0.0168	1.189		79.85	0.0168	1.156	
$^4I_{11/2}\rightarrow^4I_{13/2}$	2711	13.34	0.0028	0.791		13.40	0.0028	0.777		13.39	0.0028	0.760	

V. Conclusion

In the present study, the glass samples of composition (25-x)P_2O_5: 10ZnO: 10Li_2O: 10PbO: 10Al_2O_3: 10Sb_2O_3: 10Y_2O_3: 15B_2O_3: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 ($^4I_{13/2}\rightarrow^4I_{15/2}$) for glass YZLLAABP (ER 01), suggesting that glass YZLLAABP (ER 01) is better compared to the other two glass systems. The transition ($^4I_{13/2}\rightarrow^4I_{15/2}$) is useful for the development of 1.5 µm broadband Amplifier

References

[1]. S.L.Meena,Structural, physical and optical properties of Pr^{3+} doped in bismuth borate glasses, Appl.Phys A 130:404(2024).
[2]. S.Mao,C.Ta,H.Wen,R.A.Talewar,Optical properties of 40ZnO-40P_2O_5-x(10Li_2O-10Nb_2O_5-0.2Pr^{3+}) glass, Results Opt.12,100429(2023).
[3]. P.P.Pawar,S.R.Munishwar,R.S.Gendam,Physical and Optical properties of Dy^{3+}/Pr^{3+} co-doped lithium borate glasses for W-LED,J.Alloys-Compd.660,347-355(2016).
[4]. R.Kumar,R.B.Rakesh,S.G.Mhatre,V.Bhatia,D.Kumar,H.Singh,S.P.Singh,A.Kumar,Thermolunescence,structural and optical properties of Ce^{3+} doped borosilicate glasses.J. Mater Sci.Mater Electron, 32, 18381-18396(2021).
[5]. M.A.Khan, R.J.Amjad, M.A.Ahmad, A.Sattar, S.Hussain, S.Yasmeen, M.R.Dousti, Structural and optical study of erbium doped borophosphate glass. Optic, 206, 16370(2020).
[6]. L. Zhang, M. Peng, G.Dong,J. Qiua,(2012).Spectroscopic properties of Sm^{3+}doped phosphate glasses, J. Mater. Res., 27, 16, 2111-2115(2012).
[7]. A.V. Deepa,P. Murygasen, P. Muralimanohar, K. Sathyamoorthy, P.V. Kumar (2019). A comparison on the structural and optical properties of different rare earth doped phosphate glass, Optik, 181,361-367(2019).
[8]. R.J.Amjad,A. Sattar, M.R.Dousti, Upconversion and 1.53µm near-infrared luminescence study of the Er^{3+}-Yb^{3+} co-doped novel phosphate glasses.Optik,200,1-5(2020).
[9]. V.R. Rao , C. Jayasankar, Spectroscopic investigaions on multi-channel visible and NIR emission of Sm^{3+} doped alkali-alkaline earth fluoro phosphate glasses. Optical Materials, **91**, 7-16(2019).
[10]. P.Mandal,S.Aditya and S. Ghosh, Optimization of rare earth(Er^{3+}) doping level in lead zinc phosphate glass through Judd-Ofelt analysis,Materials Chem. And Phy., 246, 122802,1-7(2020).
[11]. R.V. Kumar, G. Venkataiah,K. Marimuthu, White light stimulation and luminescence studies on Dy^{3+} doped Zincborophosphate glasses. Physica B 457,287-295(2015).
[12]. Y Chen, GH Chen, XY Liu and T Yang, Enhanced up – conversion luminescence and optical thermometry characteristics of Er^{3+}/ Yb^{3+} co-doped transparent phosphate Glass Ceremics, Journal of luminescence 195,314-320(2018).
[13]. Siti Amlah, M. Azmi, M.R. Sahar, S.K. Ghoshal, R. Arifin, Modification of structural and physical properties of samarium doped zinc phosphate glasses due to the inclusion of nickel oxide nanoparticles, Journal of Non crystalline Solids 411,53-58(2015).
[14]. C.A.G. Kalnins, N.A. Spooner, H. Ebendorff-Heidepriem and T.M. Monro (2013). Luminescent properties of fluoride phosphate glass for radiation dosimetry. Opt. Mater. Express 3 (7), 960-967.
[15]. L.Zhang,Y.Xia,X.Shen,W.Wei, Concentration dependence of visible luminescence from Pr^{3+} doped phosphate glasses, Spectrochim,Acta A Mol.Biomol.Spectrosc.206,454-459(2019)
[16]. P.G. Pavani,K. SadhanaV.C. Mouli, Optical, physical and structural studies of boro-zinc tellurite glasses, Physica B: Condensed Matter, 406, 7, 1247(2011).
[17]. S.Mitra,S.Jana,Intense orange emission in Pr3+ doped lead phosphate glass,J.Phys.Chem.85,245-253(2015).
[18]. S.L.Meena,Structural and FTIR analysis of Sm^{3+} ions doped ytterbium zinc lithium lead sodalime cadmium phosphate glasses,Int.J.Innov.Res.Sci.Eng.Tech.12,10811-10820(2023).
[19]. Ch.Basavapoornima,C.R.Kesavulu,T.Maheswari,W.Pecharapa,S.Rani,Spectralcharacteristics of Pr^{3+}-doped lead phosphate glasses for optical display device and gain media applications, 2279, 060002 (2020).
[20]. Kh.S.Shaaban,E.A.Wahab,A.A.,Ei-Maaref,M.Abdelawwad,E.R.Shaaban,ElS.Yousef, H.Wilke, H.Hillmer, J.Borcsok,Juudd-Ofelt analysis and physical properties of erbium modified cadmium lithium gadolinium silicate glasses,J.Mat.Sci.10854-020-03065-8,4686-4996(2020).
[21]. G.R.Kumar,C.S. Rao, Influence of Bi_2O_3, Sb_2O_3 and Y_2O_3 on optical properties of Er_2O_3-doped CaO–P_2O_5–B_2O_3 glasses, , Bull. Mater. Sci. 43,71, 1-7(2020).
[22]. Kaur,H.,Kaur,N.,Kumar,D.,Singh,S.P.(2024).Gamma irradiated Er^{3+} ions Li_2O-BaO-B_2O_3-P_2O_5 glasses: Structural, optical and thermoluminescence glow curve analysis,Ceraam.Int.50(9),36731-36746
[23]. Naseer,K.A.,Marimuthu,K.(2021).The impact of Er/Yb co-doping on the spectroscopic performance of bismuth borophosphate glasses for photonic applications,Vacuum,183,109788.
[24]. Z,Zhao, B.Zhang, Y.Gong, Y.Ren, M.Huo, Y.Wang, Concentration effect of Yb^{3+} ions on the spectroscopic properties of high-concentration Er^{3+}/Yb^{3+} co-doped phosphate glasses.J.Mol.Struct.1216,128322(2020).

[25]. Gorller-Walrand, C. and Binnemans, K. (1988). Spectral Intensities of f-f Transition. In: Gshneidner Jr., K.A. and Eyring,L., Eds., Handbook on the Physics and Chemistry of Rare Earths, Vol. 25, Chap. 167, North-Holland, Amsterdam, 101-264.
[26]. Sharma, Y.K., Surana, S.S.L. and Singh, R.K. (2009). Spectroscopic Investigations and Luminescence Spectra of Sm^{3+} Doped Soda Lime Silicate Glasses. Journal of Rare Earths, 27, 773.
[27]. Judd, B.R.(1962).Optical absorption intensities of rare earth ions,Phys.Rev.127,750-761.
[28]. Ofelt,G.S. (1962). Intensities of crystal spectra of rare earth Ions, Chem.Phys37, 511-520.
[29]. S.L.Meena, Spectral and Thermal analysis of praseodymium doped bismuth borate glasses for thermionic applications, IOSR J.Appl.Phys.16,20-27(2024).
[30]. Q. Wei, X. Z. Li, Z. J. Wang, X. F. Long, Growth and spectroscopic properties of Pr^{3+} doped $Sr_3Y_2(BO_3)_4$ crystal, Mat. Res. Innov. 13, 2-6 (2009).