Spectroscopic characterization of Er³⁺ doped lead zinc phosphate glass via Judd–Ofelt analysis

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Abstract. Lead zinc phosphate (LZP) glass doped with 0.6% Er³⁺ is prepared by a conventional melt quenching technique. Judd–Ofelt (JO) analysis is carried out with an absorption spectrum of the as-prepared glass generating the set of JO parameters: $\Omega_2 = 2.75 \times 10^{-20} \text{ cm}^{-2}$, $\Omega_4 = 2.71 \times 10^{-20} \text{ cm}^{-2}$ and $\Omega_6 = 0.44 \times 10^{-20} \text{ cm}^{-2}$. The magnitude of the spectroscopic quality factor (χ_p) defined by Ω_4/Ω_6 obtained in our sample turns out to be 6.16 which is 2–10 times larger than that of other Er³⁺ doped glasses. The lifetime of $^4I_{13/2}$ and $^4I_{11/2}$ levels estimated via the JO parameters is found to provide superior values of 7.25 and 5.51 ms, respectively. The elevated value of Ω_4/Ω_6 along with the estimated 100% luminescence branching ratio of $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition implies that Er³⁺ doped LZP can be a promising material as a laser active medium.

Keywords. Phosphate glass; erbium doping; Judd–Ofelt parameters; spectroscopic quality factor; laser active medium.

1. Introduction

Efficient lasers with a wide range of wave lengths have been developed using glass and glass ceramics as promising solid state hosts [1]. In a disordered glassy matrix, lanthanides with a 4fⁿ electronic configuration are potential candidates for the fabrication of an upconversion solid state laser [2–4] for their higher order nonlinear susceptibility [5]. In recent years rare earth (RE) doped phosphate glasses, especially ZnO based glasses [6], have drawn substantial attention as a fibre optic waveguide laser and amplifier for their good chemical durability, thermal stability and transparency [7]. For example, reports based on the optical properties of lead zinc phosphate (LZP) glass doped with RE, e.g., Dy³⁺ [8], Sm³⁺ [9] and Tb³⁺ [10], are available in the literature. But, reports on such a LZP system doped with Er are scarce although there are studies on Er doped zinc phosphate glass containing nanoparticles [11,12], Pb free zinc phosphate glass [7] etc. In the field of laser application, it has to be kept in mind that for a solid state laser active medium, spectroscopic quality factor (χ_p) is a crucial parameter to determine the efficiency of lasing action. Judd–Ofelt (JO) analysis [13,14] is a powerful tool to predict χ_p along with other important radiative parameters, such as radiative transition probability (A), lifetime of an excited state (τ_R), luminescence branching ratio (β) etc. The correct magnitude of these important radiative parameters of emitting states of the RE atoms is reliably estimated using JO parameters. Experimentally found radiative decay constants are often mixed up with other non-radiative paths, and hence are inaccurate and not reliable.

In this communication, we report on JO analysis for the as-prepared LZP system with erbium (Er³⁺) doping (0.6%). The χ_p and other relevant transition parameters such as A , τ_R and β are estimated and compared with other solid state glass host systems doped with Er³⁺. Almost a tenfold higher magnitude of χ_p and a better value of the other transition parameters in our Er³⁺: LZP as-prepared glass promise this system to be a superior laser active medium, especially in the infrared regime.

2. Materials and methods

2.1 Glass preparation

Er³⁺ doped LZP glass (P₂O₅)₅₅(ZnO)₃₀(PbO)_{15-x}(Er₂O₃)_x, with $x = 0.3$, was prepared using laboratory grade ZnO, PbO, (NH₄)H₂PO₄ and Er₂O₃ (from Aldrich) with an oxygen to phosphorous ([O]/[P]) and phosphorous to zinc ([P]/[Zn]) ratio maintained at 2.90 and 3.66, respectively.

The above mentioned powders were mixed in appropriate stoichiometry, heated up to 800°C in an alumina crucible and left undisturbed for 30 min. The mixture becomes a liquid which is quenched quickly using an iron pressing module.

The density (ρ) of the glasses was determined via Archimedes' principle to an accuracy of $3.432 \pm 0.001 \text{ g cm}^{-3}$. The molar volume $V_m (= W_m/\rho)$ was calculated to be $38.83 \text{ cm}^3 \text{ mol}^{-1}$, W_m being formula weight. Details of preparation and density measurement can be found in our previous report [15].

Figure 1. (a) SEM images of the Er^{3+} :LZP sample and (b) EDX spectrum confirming the inclusion of Er^{3+} in the glass matrix.

2.2 Physical property characterization

A differential thermal analyser (DTA) with a 10 K min^{-1} sweep rate in the temperature range of $200\text{--}800^\circ\text{C}$ indicates glass transition temperature at $\sim 150^\circ\text{C}$ and the crystallization temperature seems to be 430°C . The amorphous nature of this as-prepared sample was confirmed by an X-ray diffraction (XRD) ($\text{Cu K}\alpha$ radiation: X'pert pro) pattern which was featureless, without any peak and reported from our group [15]. The scanning electron microscope (SEM) image of the as-prepared sample shown in figure 1a depicts no signature of grain growth, characteristic of its amorphous nature. Figure 1b shows the EDX spectrum confirming the Er inclusion in the glass matrix. The details of microscopy, composition, structure obtained *via* SEM and XRD and bonding-related information of the sample collected through Fourier transform infrared (FTIR) studies of the sample can be found elsewhere [15].

2.3 Optical properties

The optical properties of the glass were investigated in the range of $300\text{--}800 \text{ nm}$ with a UV–VIS spectrophotometer. The refractive index (n) was calculated from the optical band gap $E_g = 4.78 \text{ eV}$, calculated from $(\alpha h\nu)^2$ vs. $h\nu$ plot [15] confirming its insulating nature. Permittivity (ϵ_r) = 4.14 and susceptibility (χ) = 5.14 are calculated from the

refractive index; molar refraction (R_m) = $19.80 \text{ cm}^3 \text{ mol}^{-1}$ and electronic polarizability (α_m) = $7.86 \text{ \AA}^3$ are obtained from the Lorentz–Lorenz equation [16], and the related details are presented in literature [15]. The molecular weight of our Er_2O_3 doped LZP glass with chemical composition $55\text{P}_2\text{O}_5\text{--}30\text{ZnO--}14.7\text{PbO--}0.3\text{Er}_2\text{O}_3$ is $M = 136.33 \text{ g}$. This chemical composition corresponding to 0.6% Er doping with a number density $N_0 = 9.3 \times 10^{19} \text{ cm}^{-3}$ will be used for JO analysis in the following section.

3. Results and discussion

3.1 Determination of JO parameters from UV–VIS spectrum

To describe the same parity f–f transitions in RE ions, JO theory [13,14] has become the centre of interest for RE spectroscopy. In fact, for some basic and preliminary level characterization of luminescent materials, this theory is being employed [17–19]. The big application of the JO theory is that by using only just three empirical parameters, Ω_λ ($\lambda = 2, 4$ and 6), prediction of several spectroscopic features like, oscillator strengths in luminescence and absorption, induced emission cross section, radiative quantum efficiency [20], luminescence branching ratios and radiative lifetime of excited-state [21] is possible. Actually, the JO theory states that electric-dipole oscillator strength or line strength, S_{ed} for lanthanide and actinide associated with an f–f optical transition is given in terms of three phenomenological intensity parameters Ω_λ [18,20]:

$$S_{\text{ed}}^{\text{cal}}(J \rightarrow J') = \sum_{\lambda=2,4,6} \Omega_\lambda \left| \langle f^n([SL]J) || U^{(\lambda)} || f^n([S'L']J') \rangle \right|^2 \quad (1)$$

where $U^{(\lambda)}$ is the irreducible tensor form of the dipole operator. The JO parameters Ω_λ ($\lambda = 2, 4$ and 6) contain radial integrals over $4f^n$ and perturbing states with opposite parity, odd order terms of the crystal field. The terms in brackets are doubly reduced matrix elements (or unit tensor operator) in intermediate (Russel-Saunders) coupling approximation. As the f electrons are well shielded by the outer 5d electrons in RE ions, the influence of the crystal field outside the RE ion acts essentially as a small perturbation. The screening of the optically active electrons from the influence of the crystal field grants the lanthanides well defined, sharp spectral features, like free ions. Within such a scenario of the screened free atom-like case, the matrix elements depend little on the host material. It is a standard practice to use the matrix elements for trivalent lanthanides in aqueous solution or LaF_3 . In our JO analysis, matrix elements are harnessed from Carnall *et al* [22].

The practicality of JO expression, i.e. equation (1) is that the line strength, $S_{\text{ed}}^{\text{cal}}(J \rightarrow J')$ of a transition can also be calculated from the absorption cross section $\sigma(\lambda)$ [23,24] with

Figure 2. UV–VIS absorption spectra of Er^{3+} :LZP ($x = 0.003$). The designation of the peaks corresponds to the excited states from the ground state $^4\text{I}_{15/2}$.

the help of the following equation [18,20]:

$$S_{\text{ed}}^{\text{meas}}(J \rightarrow J') = \frac{3ch(2J+1)}{8\pi^3 e^2 \bar{\lambda}} n \left[\frac{3}{n^2 + 2} \right]^2 \int_{\text{manifold}} \sigma(\lambda) d\lambda \quad (2)$$

where J and J' indicate the initial and final manifolds, m is the electron mass, c is the speed of light, h is Planck's constant, $\bar{\lambda}$ is the barycenter wavelength of the $J \rightarrow J'$ absorption band and n is the refractive index at $\bar{\lambda}$. The absorption cross section $\sigma(\lambda)$ can be calculated from the absorption spectrum using the formula [24]

$$\sigma(\lambda) = \frac{1}{N_0 d} \ln \frac{I_0(\lambda)}{I(\lambda)} = \frac{2.303 (\text{O.D.})}{N_0 d},$$

where

$$\text{O.D.} = \log \frac{I_0(\lambda)}{I(\lambda)}$$

is the optical density (absorbance or absorptivity), N_0 and d are the site density of the optically active ions (i.e., Er^{3+}) in the crystal and sample thickness respectively. The measured d of the sample is 1.1 mm. Experimentally calculated line strengths $S_{\text{ed}}^{\text{meas}}$ (cf. equation (2)) can be used together with JO expression $S_{\text{ed}}^{\text{cal}}$ (equation (1)) to obtain JO parameters *via* fitting $S_{\text{ed}}^{\text{meas}}$ a least square difference sum with $S_{\text{ed}}^{\text{cal}}$.

Figure 2 shows the UV–VIS absorption spectrum. The ground state of Er^{3+} is designated by $^4\text{I}_{15/2}$. Absorption peaks corresponding to the ground (initial) state to different excited (final) states which are designated in the parentheses are centred at 364 nm ($^4\text{G}_{9/2}$), 376 nm ($^4\text{G}_{11/2}$), 406 nm ($^2\text{H}_{9/2}$), 450 nm ($^4\text{F}_{3/2,5/2}$), 486 nm ($^4\text{F}_{7/2}$), 519 nm ($^2\text{H}_{11/2}$) and 544 nm ($^4\text{S}_{3/2}$). For the calculation of line strength from the spectrum in JO analysis, $^4\text{G}_{9/2}$, $^4\text{G}_{11/2}$, $^4\text{F}_{7/2}$ and $^2\text{H}_{11/2}$ peaks

are chosen to extract the integrated absorbance. Table 1 shows the matrix elements [22] and the line strengths $S_{\text{ed}}^{\text{meas}}$ obtained *via* equation (2) in connection with different absorption manifolds. Now

$$\begin{aligned} \sigma^2 &= \sum_{i=1}^N (S_i^{\text{meas}} - S_i^{\text{cal}})^2 \\ &= \sum_{i=1}^N \left(S_i^{\text{meas}} - \sum_{j=1}^3 U_{ij} \Omega_j \right)^2 \end{aligned}$$

is constructed with the values of $S_{\text{ed}}^{\text{meas}}$ where U_{ij} are the matrix elements (cf. table 1) [18]. The index i corresponds to different $J \rightarrow J'$ transitions and $N = 4$, the number of transitions to fit. JO parameters Ω_j 's ($j = 1, 2$ and 3) have to be determined *via* a least square fitting which is equivalent to the condition [18] $\partial(\sigma^2)/\partial\Omega_k = 0$ for each $k = 1, 2$ and 3 .

This condition leads to three equations. Solving them *via* a matrix method Ω_j 's can be obtained as a column matrix [25] $\Omega_0 = [\mathbf{U}^\dagger \mathbf{U}]^{-1} \mathbf{U}^\dagger \mathbf{S}^{\text{cal}}$ where $\mathbf{S}^{\text{cal}}$ is an $N \times 1$ column matrix containing $S_{\text{ed}}^{\text{meas}}$ (cf. table 1) as its elements and the $N \times 3$ matrix $\mathbf{U}$ is constructed with the reduced matrix elements (cf. table 1), $\mathbf{U}^\dagger$ is classical adjoint of $\mathbf{U}$. The JO parameters achieved this way are shown in table 1. Once JO parameters are obtained, $S_{\text{ed}}^{\text{cal}}$ can be calculated by substituting these Ω_j parameters in equation (1). The values of $S_{\text{ed}}^{\text{cal}}$ are shown along with $S_{\text{ed}}^{\text{meas}}$ in table 1 displaying a good quantitative agreement between $S_{\text{ed}}^{\text{cal}}$ and $S_{\text{ed}}^{\text{meas}}$. The root mean square (rms) deviation which is the measure of overall quality of the fitting of the calculated to experimental line strengths is defined as [17,23]

$$\delta_{\text{rms}} = \sqrt{\sum_{i=1}^N (S_i^{\text{meas}} - S_i^{\text{cal}})^2 / (N - 3)}.$$

The magnitude of $\delta_{\text{rms}} = 0.2441 \times 10^{-20} \text{ cm}^2$ indicates a reasonably good fitting.

JO parameters obtained for Er^{3+} in our material host are $\Omega_2 = 2.75 \times 10^{-20} \text{ cm}^{-2}$, $\Omega_4 = 2.71 \times 10^{-20} \text{ cm}^{-2}$ and $\Omega_6 = 0.44 \times 10^{-20} \text{ cm}^{-2}$. In table 2, JO parameters for Er^{3+} in other different hosts are listed for comparison with our work. The magnitude of Ω_4 obtained in our work is somewhat on the higher side than the Ω_4 values in other host materials (cf. table 2). However, for Ω_6 , the behaviour is opposite, i.e., Ω_6 is slightly lower than the average of other studies as evident. However, the magnitude of Ω_2 falls nearly at the middle of the range. JO parameters bear the signature of bonding and the local structure around the RE ion and its bonding in the host matrix with the ligands. According to earlier studies on Er in different environments, the parameter Ω_2 is known to be linked with the degree of covalency [34] of the RE–ligand bond in the host matrix and supposed to be strongly influenced by the local symmetry around the RE ion whereas the Ω_6 parameter is related to the overlap integral between 4f and 5d orbitals [35]. A slightly lower value of Ω_6 may imply a weaker overlap between 4f and 5d orbitals. The parameters Ω_4 and Ω_6 are believed to provide the fingerprint of the bulk

Table 1. Matrix elements for Er(III), calculated and measured values of line strength for the Er³⁺:LZP sample.

Transition from $^4I_{15/2}(J)$ to J'	$ \langle U^{(2)} \rangle ^2$	$ \langle U^{(4)} \rangle ^2$	$ \langle U^{(6)} \rangle ^2$	$\bar{\lambda}$ (nm)	Line strength ($S \times 10^{-20} \text{ cm}^{-2}$)	
					Calculated ($S_{\text{ed}}^{\text{cal}}$)	Measured ($S_{\text{ed}}^{\text{meas}}$)
$^2H_{11/2}$	0.7125	0.4125	0.0925	519	3.1205	3.4925
$^4F_{7/2}$	0	0.1469	0.6266	486	0.6757	0.6761
$^4G_{11/2}$	0.9183	0.5262	0.1172	376	4.0061	3.7174
$^4G_{9/2}$	0	0.2416	0.1235	364	0.7102	0.7035

Ω_{λ} and $\delta_{\text{rms}} (\times 10^{-20} \text{ cm}^{-2})$: $\Omega_2 = 2.75$, $\Omega_4 = 2.71$, $\Omega_6 = 0.44$ and $\delta_{\text{rms}} = 0.2441$.

Table 2. Comparison of Ω_{λ} and χ_p for Er³⁺ with the LZP host (our work) and different other host materials.

Material	$(\Omega_{\lambda} \times 10^{-20} \text{ cm}^{-2})$			Ω_4/Ω_6	Ref.
	Ω_2	Ω_4	Ω_6		
LZP:Er ³⁺	2.75	2.71	0.44	6.16	This work
Germanate	4.81	1.41	0.48	2.94	[26]
NaYF ₄ :Er ³⁺ /PMMA	2.16	1.40	0.64	2.19	[24]
BaGd ₂ ZnO ₅ :Er ³⁺ /PMMA	1.22	1.10	0.54	2.04	[24]
Er ³⁺ :Na–Pb–Ge–tellurite	10.8	1.17	4.32	0.27	[27]
Phosphate	1.68	2.68	1.60	1.68	[28]
Tellurite	5.54	1.90	0.88	2.16	[29]
LiYF ₄	1.92	0.26	1.96	0.13	[30]
Er _{0.0038} Y _{0.498} Zr _{0.498} O _{1.745}	2.92	0.78	0.57	1.37	[31]
Er ³⁺ :LYB crystal	7.67	1.45	0.82	1.47	[32]
Er ³⁺ garnets	0.74	0.33	1.02	0.32	[33]

properties, e.g., viscosity and rigidity of the material [34]. It is also reported that Ω_4 and Ω_6 are strongly influenced by the ionic packing ratio of the host [36]. Therefore, somewhat diminished values of Ω_6 might be related to the properties of the LZP glass host, e.g., reduced ionic packing and rigidity. But the reason for the slightly increasing trend of Ω_4 , contrary to Ω_6 , is unclear. However, the parameter which turns out to be most noticeable in our study is $\chi_p = \Omega_4/\Omega_6$. The parameter χ_p was first introduced by Kaminiskii [37] and is critically important to predict stimulated emission in the laser active material. The value of χ_p found in our material is 6.16 (cf. table 2). This is 2–10 times higher than χ_p for Er³⁺ among a variety of other hosts (cf. table 2). It is crucial to observe that more the value of χ_p the more intense would be the stimulated emission intensity. So the material LZP glass can be a good host for Er³⁺ as a potential candidate to be a laser active medium. JO parameters are very helpful in predicting important parameters related to radiative properties. In the following section, useful spectroscopic parameters, like spontaneous emission probability (A), radiative lifetime (τ_R) and branching ratio (β) of the excited states are calculated.

3.2 Radiative properties

Spontaneous electric dipole radiative transition probability of an excited state (J') can be calculated using equation (3)

[13,14]. By dint of the JO parameters obtained *via* the analysis, $S_{\text{ed}}(J \rightarrow J')$ required in equation (3) can be obtained from equation (1). Of course the reduced matrix elements $|\langle f^N([SL]J) || U^{(\lambda)} || f^N([S'L']J) \rangle|^2 (= |\langle U^{(\lambda)} \rangle|^2)$ have to be known for the specific transition and they are taken from Carnall *et al* [38].

$$A(J' \rightarrow J) = \frac{64\pi^4 e^2}{3h(2J' + 1)\bar{\lambda}^3} n \left[\frac{n^2 + 2}{3} \right]^2 S_{\text{ed}}(J \rightarrow J') \quad (3)$$

The radiative lifetime (τ_R) of an emitting state is given by equation (4) [39] which is the reciprocal of the total transition probability of the emitting state. The summation is taken over all the low lying manifolds permitted for transition.

$$\tau_R^{-1} = \sum_J A(J' \rightarrow J) \quad (4)$$

The fluorescence branching ratio $\beta_{J' \rightarrow J}$ can be used to predict the relative intensity of the emission lines originating from a given excited state and is obtained from equation (5) [39].

$$\beta_{J' \rightarrow J} = \tau_R A(J' \rightarrow J) \quad (5)$$

These radiative parameters A , τ_R and β are estimated for our Er³⁺:LZP as-prepared sample and presented in table 3.

Table 3. Spontaneous emission probability (A), radiative lifetime (τ_R) and branching ratio (β) calculated for Er^{3+} in LZP glass.

Transition	$\bar{\lambda}$ (nm)	A (s^{-1})	τ_R (ms)	β (%)
$^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$	1540	137.9	7.25	100.0
$^4\text{I}_{11/2} \rightarrow ^4\text{I}_{15/2}$	987	152.4		83.9
$\rightarrow ^4\text{I}_{13/2}$	2752	29.1	5.51	16.1
$^4\text{I}_{9/2} \rightarrow ^4\text{I}_{15/2}$	808	587.9		92.1
$\rightarrow ^4\text{I}_{13/2}$	1699	48.4		7.6
$\rightarrow ^4\text{I}_{11/2}$	4442	2.1	1.57	0.3

The radiative lifetime τ_R of the $^4\text{I}_{13/2}$ excited state is estimated to be the highest, 7.25 ms compared to $^4\text{I}_{11/2}$ and $^4\text{I}_{9/2}$ whose lifetimes are 5.51 and 1.57 ms, respectively. All of these states are metastable with $\tau_R \sim \text{ms}$. A recent work has reported that τ_R for $^4\text{I}_{13/2}$, $^4\text{I}_{11/2}$ and $^4\text{I}_{9/2}$ levels to be 3.89, 4.11 and 2.49 ms, respectively [2]. Compared to this report, our result indicates that $^4\text{I}_{13/2}$ and $^4\text{I}_{11/2}$ levels possess larger lifetimes. In fact, the radiative lifetime obtained by us for the $^4\text{I}_{13/2}$ level of Er^{3+} in the LZP glass host is comparable to the upper limit of τ_R (7.87 and 7.53 ms) among the tabulated τ_R values at ref. [40] for Er^{3+} in a variety of glass hosts.

Two crucial parameters to predict the possibility of laser emission are the fluorescence branching ratio and radiative lifetime. The $^4\text{I}_{13/2}$ state with $\tau_R \approx 7.25$ ms is a metastable one. Such a large lifetime will allow this level to undergo population inversion. In addition, the highest branching ratio of 100% for the $^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transition points to high possibility of efficient laser emission at $\approx 1.5 \mu\text{m}$. In fact the luminescence branching ratio is a critical parameter to attain stimulated emission from a specific transition. Also a high spontaneous emission probability of 137.9 provides a better chance to obtain laser emission. $\chi_p = \Omega_4/\Omega_6$ plays an important role in the following manner. For lasing action in Er^{3+} , the $^4\text{I}_{9/2}$ level is employed as the pumping level. The line strength for $^4\text{I}_{15/2} \rightarrow ^4\text{I}_{9/2}$ absorption is practically dominated by Ω_4 because $|\langle U^{(2,6)} \rangle|^2$ is insignificant as compared to $|\langle U^{(4)} \rangle|^2 = 0.1587$ [38]. Population inversion occurs at $^4\text{I}_{13/2}$ after transition from the $^4\text{I}_{9/2}$ level. The lasing action in the infrared regime ($1.5 \mu\text{m}$) is possible for the $^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transition which is mainly determined by Ω_4 and Ω_6 due to tiny $|\langle U^{(2)} \rangle|^2$ compared to $|\langle U^{(4,6)} \rangle|^2$. Therefore Ω_4/Ω_6 decides how effectively this entire process can happen. As already discussed, Ω_4/Ω_6 is quite high in our Er^{3+} :LZP system, and hence stands as a potential candidate for an infrared laser source.

4. Conclusion

The LZP glasses doped with 0.6% Er are characterized by SEM-EDX and UV-VIS spectroscopy confirming their glassy nature with erbium incorporation. The JO analysis carried

over the Er^{3+} :LZP as-prepared sample provides Ω_2 within the range but a slightly higher value of Ω_4 and somewhat diminished Ω_6 , the values being $\Omega_2 = 2.75 \times 10^{-20} \text{ cm}^{-2}$, $\Omega_4 = 2.71 \times 10^{-20} \text{ cm}^{-2}$ and $\Omega_6 = 0.44 \times 10^{-20} \text{ cm}^{-2}$. The magnitude of the χ_p defined by Ω_4/Ω_6 obtained in our sample turns out to be 6.16 which is order of magnitude larger than other Er^{3+} doped glasses. Calculation of important spectroscopic parameters indicates that $^4\text{I}_{13/2}$ and $^4\text{I}_{11/2}$ levels possess superior lifetimes of 7.25 and 5.51 ms, respectively. The relatively large value of the χ_p and the 100% luminescence branching ratio of $^4\text{I}_{13/2} \rightarrow ^4\text{I}_{15/2}$ transition indicate that efficient laser emission can occur at $1.5 \mu\text{m}$ in our Er^{3+} doped LZP as-prepared glass.

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