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Spectroscopic properties of Er^{3+} ions in cadmium and alkali cadmium borosulphate glasses

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Abstract. Spectroscopic properties of Er^{3+} : CBS ($CdSO_4 + B_2O_3$ and $R_2SO_4 + CdSO_4 + B_2O_3$, $R_2SO_4 = Li_2SO_4 \cdot H_2O$, Na_2SO_4, K_2SO_4 and $Gd_2(SO_4)_3 \cdot 8H_2O$) glasses are reported. The assigned energy level data of $Er^{3+}(4f^{11})$ in these glasses are analysed in terms of a parametrized model Hamiltonian. The standard deviations of the data fits are between 39 and 47 cm^{-1} so that the energy level schemes of the $Er^{3+}(4f^{11})$ ions in borosulphate (CBS) glasses are reasonably well reproduced. Radiative properties for the fluorescent levels of Er^{3+} : CBS glasses are determined by using the Judd–Ofelt theory. The potential laser transitions are identified with the help of predicted radiative properties which are compared and discussed with similar results.

Keywords. Erbium doped glasses; optical absorption; oscillator strengths; radiative properties.

PACS Nos 81·40; 81·60; 78·20; 71·55

1. Introduction

The optical properties of Er^{3+} ions have been studied in numerous crystalline hosts [1–4], glass media [5–9] and solutions [10, 11].

Laser action of trivalent erbium in silicate glasses was first obtained by Snitzer and Woodcock [12]. The lasing wavelength of 1540 nm raised strong interest for reasons of eye safety and easy detection. The lamp pump efficiency of 1.7% with a threshold of 5J was reported by Gapontsev *et al* [13] in phosphate glass. The C.W. laser action of Er^{3+} in silica fibers via argon laser pumping was achieved by Mears *et al* [14].

Among rare-earth ions, Er^{3+} is one of the most popular ions since its laser oscillation is utilized as a fiber amplifier of Er doped silica at 1·55 μm [15]. Moreover, it exhibits three fluorescent lines, blue, green and red in the visible region. Also the green-upconversion emission at 0·55 μm has been observed in Er:oxide glasses [16]. The emission properties of these transitions depend on the ligand field of the rare-earth ions.

The Judd–Ofelt theory [17, 18] is helpful in estimating the probability of the forced electric dipole transitions of rare-earth ions in various environments. In the Judd–Ofelt theory, three parameters (Ω_λ, $\lambda = 2, 4, 6$) appear and they can be determined experimentally from the measurements of absorption spectra and refractive index of host material. From these parameters several important optical properties can be evaluated [5–9]. In order to estimate the laser or upconversion efficiency of a particular transition, it is important to know the relation between the glass composition and the Ω_λ.

In this paper we present the investigations carried out on the spectroscopic properties of Er^{3+} : CBS glasses to understand the behaviour of rare-earth ions in these hosts, and to augment the earlier results on Er^{3+} : glasses [5–9].

2. Theory

2.1 *Energy level analyses*

The behaviour of rare earth ions in glasses is similar to that of rare earth ions in inorganic crystals of low symmetry except for inhomogeneous broadening of the spectra because of the multiplicity of rare earth sites in glasses [19]. Optical absorption spectra of triply ionized rare earth ions originate from the transitions between levels of the $4f^n$. The model Hamiltonian which describes the position of these levels for Ln^{3+} ions is written as [4, 20]

$$\begin{aligned} H_{\mathrm{FI}} = & E_{\mathrm{avg}} + \sum_k F^k \hat{f}_k + \xi_{s0}\hat{A}_{s0} + \alpha\hat{L}(\hat{L}+1) + \beta\hat{G}(\hat{G}_2) + \gamma\hat{G}(R_7) \\ & + \sum_i T^i\hat{t}_i + \sum_k P^k\hat{p}_k + \sum_j M^j\hat{m}_j, \end{aligned} \tag{1}$$

where $k = 2, 4, 6$; $i = 2, 3, 4, 6, 7, 8$; $j = 0, 2, 4$; and the operators $(\hat{f}_k, \hat{A}_{s0}, \hat{L}, \hat{G}, \hat{t}_i \hat{p}_k, \hat{m}_j)$ and their associated parameters $(E_{\mathrm{avg}}, F^k, \xi_{s0}, \alpha, \beta, \gamma, T^i, P^k$ and $M^j)$ are written according to conventional notation and meaning (with respect to the interactions they represent [4, 20]). The parametric fits are carried out using precisely the same methodologies and strategies employed in our earlier work on Er^{3+} doped crystal free-ion energy level analyses [2–5]. The $4f^{11}$ energy-level structure of Er^{3+} ion was analysed by diagonalizing the complete SLJ basis set. The quality of the fit is estimated by the root mean square deviation, σ, which is defined as

$$\sigma = \left\{ \left[\sum_i^N (E_i^{\mathrm{obs}} - E_i^{\mathrm{calc}})^2 \right] \Big/ N \right\}^{1/2}, \tag{2}$$

where E_i^{obs} and E_i^{calc} are the observed and calculated energies, respectively, for level i and N denotes the total number of levels included in the energy-level fit.

2.2 *Judd–Ofelt analyses and radiative properties*

By employing least-squares fitting of the measured spectral absorbance according to the Judd–Ofelt theory, the characteristic intensity parameters, Ω_λ, were estimated as detailed for Er:glasses [5–9]. From Ω_λ, the radiative properties for fluorescent levels of Er : CBS glasses are determined as detailed in ref. [5–9].

3. Experimental

One mol % of Er^{3+} : CBS (CdBS, *R*CdBS, R = Li, Na, K and Gd) glasses were prepared by melting the respective compositions as shown below in a porcelain crucible at 800°C for 10–15 min:

CdBS : $49CdSO_4 + 50B_2O_3 + 1Er_2(SO_4)_3 \cdot 8H_2O$,
LiCdBS : $10Li_2SO_4 \cdot H_2O + 39CdSO_4 + 50B_2O_3 + 1Er_2(SO_4)_3 \cdot 8H_2O$,
NaCdBS : $10Na_2SO_4 + 39CdSO_4 + 50B_2O_3 + 1Er_2(SO_4)_3 \cdot 8H_2O$,
KCdBS : $10K_2SO_4 + 39CdSO_4 + 50B_2O_3 + 1Er_2(SO_4)_3 \cdot 8H_2O$,
GdCdBS : $1Gd_2(SO_4)_3 \cdot 8H_2O + 48CdSO_4 + 50B_2O_3 + 1Er_2(SO_4)_3 \cdot 8H_2O$.

The glasses were annealed at 300°C for 20–30 min. Good optical quality glasses of 0·8 – 1·5 mm thickness and 1·5 – 2·5 cm^2 area have been chosen for the measurements.

Optical measurements were made using Hitachi U-3400 spectrophotometer in the UV–VIS–NIR region (300 nm to 2500 nm) at room temperature. The refractive indices (n) for these glasses were measured using an Abbe refractometer at sodium wavelength.

4. Results and discussion

4.1 *Absorption spectra and energy level analysis*

The absorption spectra only for Er : CdBS glass is shown in figure 1 as the spectra for other glasses (Er : *R*CdBS) are very similar. The band positions and intensities closely resemble the absorption spectra of Er^{3+} ions in glass media [5–9], though there is a slight variation in relative positions and intensities of the bands. In all the five glasses, the transitions $^4I_{15/2} \rightarrow {}^4I_{13/2,\,11/2,\,9/2}$, $^4F_{9/2}$, $^4S_{3/2}$, $^2H_{11/2}$, $^4F_{7/2,\,5/2,\,3/2}$, $^2H_{9/2}$, $^4G_{11/2}$ and $^4G_{9/2}$ are located and assigned. In Er^{3+} : CdBS and GdCdBS glasses, $^4I_{15/2}$ to $^4G_{11/2}$ and $^4G_{9/2}$ are missing due to strong absorption near UV region.

The wavenumbers of the observed bands are presented in table 1 alongwith the assignments for all the five borosulphate glasses. The parameters obtained by varying the free-ion parameters, eq. (1), to minimize the r.m.s. deviation (σ) between the observed and calculated energy values (eq. (2)) for Er^{3+} : CBS glasses are given in table 2. The calculated energy values are the eigenvalues obtained by diagonalizing the $Er^{3+}(4f^{11})$ energy matrix using the corresponding parameters given in table 2. The σ values of ±40,

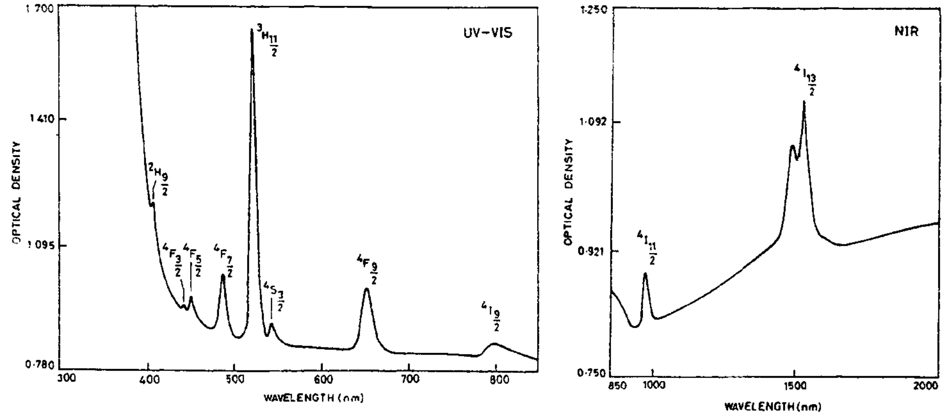

Figure 1. Absorption spectra of Er^{3+} : cadmium borosulphate glass.

Table 1. Observed energies (E, in cm^{-1}) and oscillator strengths (f, $\times 10^{-6}$) for Er^{3+} : CBS glasses*.

	CdBS		LiCdBS		NaCdBS		KCdBS		GdCdBS	
Level	E	f	E	f	E	f	E	f	E	f
$^4I_{15/2}$	0	—	0	—	0	—	0	—	0	—
$^4I_{13/2}$	6539	11·56	6524	10·69	6536	3·15	6536	11·01	6536	4·68
$^4I_{11/2}$	10275	3·86	10263	2·86	10291	0·53	10263	1·80	10263	1·79
$^4I_{9/2}$	12552	1·05	12553	0·28	12544	0·08	12553	0·43	12549	0·76
$^4F_{9/2}$	15354	13·33	15361	3·56	15361	5·57	15354	7·27	15361	5·27
$^4S_{3/2}$	18413	1·40	18457	0·30	18433	0·21	18369	1·35	18433	0·66
$^2H_{11/2}$	19205	59·50	19216	2·41	19216	4·07	19216	63·63	19216	27·44
$^4F_{7/2}$	20500	12·75	20530	1·10	20530	1·32	20530	8·81	20517	5·45
$^4F_{5/2}$	22207	1·59	22237	0·11	22222	0·19	22222	1·00	22207	0·35
$^4F_{3/2}$	22640	0·71	22457	0·07	22543	0·10	22594	0·68	22543	0·24
$^2H_{9/2}$	24691	—	24600	0·12	24600	0·29	24618	2·40	24528	—
$^4G_{11/2}$	—	—	26434	1·07	26399	4·51	26455	77·01	—	—
$^4G_{9/2}$	—	—	27457	—	27510	0·44	27480	5·38	—	—
N	11	9	13	11	13	12	13	12	11	9
σ	±40	±0·65	±46	±0·93	±43	±0·39	±39	±1·47	±47	±0·27

*For glass title abbrevations see § 3.
The value of σ represent the r.m.s. deviation between observed and calculated values given by eq. (2).

Table 2. Best fit free-ion parameters and hydrogenic ratios for Er^{3+} : CBS glasses*.

Parameter	CdBS	LiCdBS	NaCdBS	KCdBS	GdCdBS
E_{avg}	35724	35774	35691	35725	35692
F^2	100081	100959	100484	100425	100763
F^4	71594	71308	70640	71155	70643
F^6	50762	51441	51044	50486	52078
α	13·50	13·10	8·00	11·60	10·00
β	−585	−480	−355	−430	−470
γ	1675	1360	1280	1400	1325
ξ	2394	2378	2387	2390	2377
F^4/F^2	0·72	0·71	0·70	0·71	0·70
F^6/F^2	0·51	0·51	0·51	0·50	0·52

*For glass title abbreviations see § 3. The parameter values, $T^2 = 647$, $T^3 = 46$, $T^4 = 80$, $T^6 = -321$, $T^7 = 462$, $T^8 = 451$, $M^0 = 3{\cdot}95$, $M^2 = 0{\cdot}56M^0$, $M^4 = 0{\cdot}38M^0$, $P^2 = 506$, $P^4 = 0{\cdot}75P^2$ and $P^6 = 0.50P^2$ are fixed.

±46, ±43, ±39 and ±47 cm^{-1} for Er^{3+} : CdBS, LiCdBS, NaCdBS, KCdBS and GdCdBS glasses, respectively, are quite reasonable.

The interaction of Er^{3+} ions with different glass compositions is estimated by the atomic parameters. Instead of individual F^2, F^4 and F^6 variations, it is convenient to consider the variations in the total (net) electrostatic $\sum_k F^k$ [5, 21] parameter value. It is found that the $\sum_k F^k$ experienced by the Er^{3+} ion in alkali cadmium borosulphates decreases as radius and atomic weight of alkali ions decreases. The order of $\sum_k F^k$ is found to be

$$\mathrm{LiCdBS}(2,23,708\,\mathrm{cm}^{-1}) > \mathrm{NaCdBS}(2,22,168\,\mathrm{cm}^{-1}) > \mathrm{KCdBS}(2,22,066\,\mathrm{cm}^{-1}).$$

It is also found that the $4f$ orbitals of Er^{3+} ions interact with the surroundings in decreasing order when CdBS glass is modified by alkali (Li, Na, K) ions as noticed from the trends of the hydrogenic ratio (F^6/F^2), but the ratio F^4/F^2 did not show any uniform trend.

4.2 *Spectral intensities and Judd–Ofelt analysis*

The oscillator strengths of the observed absorption bands are determined experimentally [5] which are tabulated in table 1. The squared reduced matrix elements, $\|U^\lambda\|^2$, required for the Judd–Ofelt analyses have been calculated from intermediate coupling approximation for all the five glasses [10, 17, 18], though the values are only slightly sensitive to the environment. Using experimental oscillator strengths, transition energies, refractive index and reduced matrix elements, the three phenomenological parameters, Ω_λ, have been evaluated by the least square fit method as carried out for energy level fits. The Ω_λ parameters for Er^{3+} : CBS glasses are presented in table 3 alongwith Ω_λ for some Er^{3+} doped systems [8, 22–24].

The oscillator strengths of the observed bands of Er^{3+} : CdBS glasses are found to be relatively higher than those found in the other four borosulphate glasses. This implies that the non-symmetric component of the electric field acting on the Er^{3+} ions in CdBS is relatively stronger than in RCdBS glasses. It is also found that the observed oscillator strengths for some transitions, $^4F_{9/2}$, $^2H_{11/2}$, $^4F_{7/2,\,5/2,\,3/2}$, $^2H_{9/2}$ and $^4G_{11/2}$, are found to increase from LiCdBS to NaCdBS to KCdBS glasses. This trend may not yield any significant information as other observed transitions such as $^4I_{13/2,\,11/2,\,9/2}$ and $^4S_{3/2}$ do not follow uniform trend. The r.m.s. deviations of ±0·65, ±0·93, ±0·39, ±1·47 and ±0·27 (table 1) for Er^{3+} : CdBS, LiCdBS, NaCdBS, KCdBS and GdCdBS, respectively, suggest the validity of the Judd–Ofelt theory.

The Judd–Ofelt parameters, Ω_λ, are compared for 24 Er^{3+} : oxide glass systems [8, 22] alongwith Er^{3+} : aquo-ion [23] and Er(dpm)$_3$ vapour [24] systems in table 3. As seen from table 3, it is found that within oxide glasses, Ω_2 varies from 0·23 (Er^{3+} : NaCdBS) to 39·62 (Er^{3+} : KCdBS), Ω_4 varies from 0·37 (Er^{3+} : LiCdBS) to 7·58 (Er^{3+} : CdBS) and Ω_6 varies from 0·24 (Er^{3+} : S–K) to 11·37 (Er^{3+} : CdBS). Maximum variation in Ω_2 value indicates that Ω_2 is more sensitive to the environment than Ω_4 and Ω_6 parameters. Out of 26 systems compared in table 3, Ω_2 takes maximum value for vapour system. In general the magnitude of Ω_λ parameters are found to be relatively higher for sulphate glasses.

4.3 *Radiative properties*

The Judd–Ofelt intensity parameters (Ω_λ) have been used to compute the radiative properties (A, A_T, τ_R, β_R and σ_a) for the fluorescent levels, $^4G_{11/2}$, $^2H_{9/2}$, $^4F_{5/2}$, $^4F_{7/2}$,

Table 3. Ω_λ ($\times 10^{-20}\,\mathrm{cm}^2$) parameters for Er^{3+} doped systems*.

	Ω_2	Ω_4	Ω_6
CdBS	38·963	7·575	11·373
LiCdBS	1·011	0·374	6·270
NaCdBS	0·226	3·425	2·822
KCdBS	39·622	1·641	10·514
GdCdBS	18·804	3·121	4·626
$MgSO_4 + K_2SO_4 + ZnSO_4$ [22]	18·68	2·35	7·15
$CaSO_4 + K_2SO_4 + ZnSO_4$ [22]	15·18	1·65	6·69
$BaSO_4 + K_2SO_4 + ZnSO_4$ [22]	18·37	1·36	9·39
$40Li_2O + 60SiO_2$ (S–Li) [8]	4·69	1·29	0·56
$40Na_2O + 60SiO_2$ (S–Na) [8]	4·37	0·83	0·27
$40K_2O + 60SiO_2$ (S–K) [8]	5·02	0·71	0·24
$40CaO + 60SiO_2$ (S–Ca) [8]	5·91	1·53	0·77
$40SrO + 60SiO_2$ (S–Sr) [8]	5·22	1·25	0·61
$40BaO + 60SiO_2$ (S–Ba) [8]	3·42	0·83	0·27
$20K_2O + 20MgO + 60SiO_2$ (S–K–Mg) [8]	6·52	1·07	0·33
$20K_2O + 20CaO + 60SiO_2$ (S–K–Ca) [8]	5·63	0·99	0·34
$20K_2O + 20SrO + 60SiO_2$ (S–K–Sr) [8]	5·64	1·05	0·30
$20K_2O + 20BaO + 60SiO_2$ (S–K–Ba) [8]	4·80	0·84	0·26
$30Li_2O + 70B_2O_3$ (B–Li) [8]	5·81	1·84	1·18
$30Na_2O + 70B_2O_3$ (B–Na) [8]	6·04	1·59	0·91
$30K_2O + 70B_2O_3$ (B–K) [8]	5·38	1·02	0·44
$30Li_2O + 60P_2O_5 + 10Al_2O_3$ (P–Li) [8]	6·42	1·64	0·78
$30Na_2O + 60P_2O_5 + 10Al_2O_3$ (P–Na) [8]	6·85	1·67	1·08
$30K_2O + 60P_2O_5 + 10Al_2O_3$ (P–K) [8]	6·94	1·84	1·10
Aquo ion [23]	1·59	1·95	1·90
$Er(dpm)_3$ vapour [24]	46·00	2·70	3·70

* References for the source of the data are given in square brackets and for details of the glass title see the text as well as corresponding references.

${}^4S_{3/2}$, ${}^4F_{9/2}$, ${}^4I_{9/2}$, ${}^4I_{11/2}$, and ${}^4I_{13/2}$ of Er^{3+} : CBS glasses [5]. The calculated individual parameter values are given in table 4 for Er^{3+} : CdBS glass. The predicted τ_R for all the fluorescent levels are given in table 5.

The transition probabilities (A) were determined from electric (S_{ed}) and magnetic (S_{md}) dipole line strengths. For many transitions, the magnitude of S_{md} is either zero or relatively much lower than S_{ed} and hence the magnitude of A is dependent only on $\sum_\lambda \Omega_\lambda \langle \| U^\lambda \| \rangle^2$. The values of $\|U^\lambda\|^2$ are independent of host while Ω_λ are host dependent. For some laser transitions like ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ and ${}^4S_{3/2} \rightarrow {}^4I_J$, the values of $\|U^2\|^2$ and $\|U^4\|^2$ were either zero or much smaller than that of $\|U^6\|^2$. For these transitions, the radiative properties varies according to Ω_6 variation. The dependence of Ω_6 on A, A_T and β_R for ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ and ${}^4S_{3/2} \rightarrow {}^4I_J$ transitions of Er^{3+} : CBS and Er^{3+} : oxide glasses [8] are shown in table 6.

The Ω_6 and in turn A, A_T and β_R change considerably for ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ when borate and silicate glasses are modified by alkali or alkaline earths (table 6). However,

Table 4. Predicted electric (S'_{ed}) and magnetic (S'_{md}) dipole line strengths, radiative (A) and total radiative (A_T) transition probabilities, branching ratios (β_R), lifetimes (τ_R) and cross-sections (σ_a) for Er^{3+} : CdBS glasses.

SLJ	$S'L'J'$	ν cm^{-1}	$S'_{ed}\times10^{22}$ cm^2	$S'_{md}\times10^{22}$ cm^2	A s^{-1}	β_R	$\sigma_\alpha\times10^{18}$ cm^2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$^4G_{11/2}$	$^2H_{9/2}$	1755	1342·973	10·6300	13	0·0001	2·542
	$^4F_{3/2}$	3806	120·618	0·0000	12	0·0001	0·491
	$^4F_{5/2}$	4239	109·767	0·0000	15	0·0001	0·497
	$^4F_{7/2}$	5946	424·816	0·0000	162	0·0011	2·701
	$^2H_{11/2}$	7241	173·971	14·1155	130	0·0009	1·469
	$^4S_{3/2}$	8033	94·653	0·0000	89	0·0006	0·813
	$^4F_{9/2}$	11092	1624·099	2·2272	4014	0·0270	19·290
	$^4I_{9/2}$	13894	280·505	0·1123	1361	0·0092	4·169
	$^4I_{11/2}$	16171	48·764	0·0116	373	0·0025	0·843
	$^4I_{13/2}$	19907	874·124	2·6659	12513	0·0842	18·668
	$^4I_{15/2}$	26446	3882·894	0·0000	129879	0·8742	109·790
	A_T for $^4G_{11/2}=148562\,s^{-1}$				τ_R for $^4G_{11/2}=6\,\mu s$		
$^2H_{9/2}$	$^4F_{3/2}$	2051	28·757	0·0000	1	0·0000	0·076
	$^4F_{5/2}$	2484	81·413	0·0000	3	0·0001	0·259
	$^4F_{7/2}$	4191	509·706	4·6512	82	0·0036	2·769
	$^2H_{11/2}$	5486	359·872	1·6582	130	0·0057	2·546
	$^4S_{3/2}$	6278	3·259	0·0000	2	0·0001	0·026
	$^4F_{9/2}$	9337	76·575	256·6590	644	0·0284	4·365
	$^4I_{9/2}$	12139	67·841	0·1232	264	0·0117	1·059
	$^4I_{11/2}$	14416	371·748	4·2299	2448	0·1082	6·963
	$^4I_{13/2}$	18152	788·806	0·0000	10238	0·4524	18·371
	$^4I_{15/2}$	24691	270·072	0·0000	8822	0·3898	8·555
	A_T for $^2H_{9/2}=22633\,s^{-1}$				τ_R for $^2H_{9/2}=44\,\mu s$		
$^4F_{5/2}$	$^4F_{7/2}$	1707	452·077	37·7000	9	0·0005	1·804
	$^2H_{11/2}$	3002	264·426	0·0000	26	0·0013	1·697
	$^4S_{3/2}$	3794	32·728	2·2190	7	0·0004	0·286
	$^4F_{9/2}$	6853	585·147	0·0000	681	0·0354	8·575
	$^4I_{9/2}$	9655	208·295	0·0000	678	0·0352	4·300
	$^4I_{11/2}$	11932	76·359	0·0000	469	0·0244	1·948
	$^4I_{13/2}$	15668	525·552	0·0000	7311	0·3800	17·608
	$^4I_{15/2}$	22207	253·970	0·0000	10060	0·5228	12·060
	A_T for $^4F_{5/2}=19241\,s^{-1}$				τ_R for $^4F_{5/2}=51\,\mu s$		
$^4F_{7/2}$	$^2H_{11/2}$	1295	984·610	0·0000	6	0·0002	2·045
	$^4S_{3/2}$	2087	4·556	0·0000	0	0·0000	0·015
	$^4F_{9/2}$	5146	87·528	17·2868	40	0·0017	0·882
	$^4I_{9/2}$	7948	624·575	6·7807	861	0·0371	8·058
	$^4I_{11/2}$	10225	391·165	0·0000	1134	0·0488	6·414
	$^4I_{13/2}$	13961	257·626	0·0000	1902	0·0818	5·768
	$^4I_{15/2}$	20500	825·685	0·0000	19296	0·8303	27·146
	A_T for $^4F_{7/2}=23239\,s^{-1}$				τ_R for $^4F_{7/2}=57\,\mu s$		
$^4S_{3/2}$	$^4F_{9/2}$	3059	29·457	0·0000	5	0·0004	0·289
	$^4I_{9/2}$	5861	345·661	0·0000	378	0·0294	6·498
	$^4I_{11/2}$	8138	92·577	0·0000	271	0·0211	2·416

(*Continued*)

Table 4. (*Continued*).

SLJ	$S'L'J'$	ν cm^{-1}	$S'_{\rm ed} \times 10^{22}$ cm^2	$S'_{\rm md} \times 10^{22}$ cm^2	A s^{-1}	β_R	$\sigma_\alpha \times 10^{18}$ cm^2
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	$^4I_{13/2}$	11874	390·793	0·0000	3549	0·2763	14·884
	$^4I_{15/2}$	18413	255·221	0·0000	8644	0·6729	15·073
	A_T for $^4S_{3/2}$ = 12846 s^{-1}				τ_R for $^4S_{3/2}$ = 77 μs		
$^4F_{9/2}$	$^4I_{9/2}$	2802	525·521	0·1263	25	0·0030	1·890
	$^4I_{11/2}$	5079	1740·954	15·2004	500	0·0602	11·456
	$^4I_{13/2}$	8815	248·200	0·0000	369	0·0445	2·807
	$^4I_{15/2}$	15354	942·575	0·0000	7404	0·8923	18·568
	A_T for $^4F_{9/2}$ = 8298 s^{-1}				τ_R for $^4F_{9/2}$ = 120 μs		
$^4I_{9/2}$	$^4I_{11/2}$	2277	218·616	39·7462	7	0·0068	0·769
	$^4I_{13/2}$	6013	830·452	0·0000	392	0·3934	6·407
	$^4I_{15/2}$	12552	139·201	0·0000	597	0·5998	2·242
	A_T for $^4I_{9/2}$ = 996 s^{-1}				τ_R for $^4I_{9/2}$ = 1004 μs		
$^4I_{11/2}$	$^4I_{13/2}$	3736	1500·623	77·3845	150	0·1189	6·341
	$^4I_{15/2}$	10275	565·437	0·0000	1109	0·8811	6·212
	A_T for $^4I_{11/2}$ = 1259 s^{-1}				τ_R for $^4I_{11/2}$ = 794 μs		
$^4I_{13/2}$	$^4I_{15/2}$	6539	1791·167	68·7794	810	1·0000	11·196
	A_T for $^4I_{13/2}$ = 810 s^{-1}				τ_R for $^4I_{13/2}$ = 1234 μs		

Table 5. Radiative lifetimes (τ_R μs) for fluorescent levels of Er^{3+} : CBS glasses.

Glass	$^4G_{11/2}$	$^2H_{9/2}$	$^4F_{5/2}$	$^4F_{7/2}$	$^4S_{3/2}$	$^4F_{9/2}$	$^4I_{9/2}$	$^4I_{11/2}$	$^4I_{13/2}$
CdBS	6	44	51	57	77	120	1004	794	1234
LiCdBS	108	113	107	97	138	358	3748	1758	2355
NaCdBS	98	197	192	150	317	376	2857	3854	4536
KCdBS	6	51	63	57	86	194	1951	870	1403
GdCdBS	14	109	128	106	192	296	2526	1911	2881

these changes are minimum in the case of S–K-alkaline earths and phosphate–alkali glasses [8]. Similar observations are noticed for $^4S_{3/2} \rightarrow {}^4F_{9/2}$ and ^4I_J transitions. Out of 20 glass systems compared in table 6, it is found that Ω_6, A, A_T and β_R are found to be maximum for CdBS glasses and minimum for S–K glasses. It is also found that Ω_6 values increase in the order of K to Na to Li modifier ions for silicate and borate glasses, whereas decreasing trend is noticed for phosphate glasses. However, non-uniform trend is noticed when potassium based silicate glasses are modified with alkaline earths. Systematic variation of Ω_6 is not found for CdBS glasses when these glasses are modified by alkali elements. Therefore, it is inconclusive to establish general trend in Ω_6 when the glass network is modified by either alkali or alkaline earths. It is also noticed that among $^4S_{3/2} \rightarrow {}^4I_J$ emission channels, $^4S_{3/2} \rightarrow {}^4I_{15/2}$ exhibits maximum and $^4S_{3/2} \rightarrow {}^4I_{11/2}$ exhibits minimum values of A and/or β_R irrespective of the type of glass compositions. However, investigations indicate that

Table 6. Judd–Ofelt parameter (Ω_6), radiative (A) and total radiative (A_T) transition probabilities and branching ratios (β_R) for Er^{3+} : glasses [8].

		$^4I_{13/2} \to$	$^4S_{3/2} \to$					
Glass	Ω_6	$^4I_{15/2}$ A/A_T	$^4F_{9/2}$ A (β_R)	$^4I_{9/2}$ A (β_R)	$^4I_{11/2}$ A (β_R)	$^4I_{13/2}$ A (β_R)	$^4I_{15/2}$ A (β_R)	A_T
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
CdBS	11·37	810	5	378	271	3549	8644	12846
			(0·000)	(0·029)	(0·021)	(0·276)	(0·672)	
LiCdBS	6·27	425	2	182	151	1997	4866	7199
			(0·000)	(0·025)	(0·021)	(0·278)	(0·676)	
NaCdBS	2·82	220	1	106	69	865	2106	3146
			(0·000)	(0·034)	(0·022)	(0·275)	(0·670)	
KCdBS	10·51	712	4	292	236	3178	7790	11501
			(0·000)	(0·025)	(0·021)	(0·276)	(0·677)	
S–Li	0·56	88	—	30	16	195	488	729
				(0·041)	(0·022)	(0·268)	(0·669)	
S–Na	0·27	60	—	15	8	89	223	334
				(0·045)	(0·022)	(0·266)	(0·667)	
S–K	0·24	59	—	13	7	79	198	297
				(0·045)	(0·023)	(0·266)	(0·666)	
S–Ca	0·77	117	—	43	24	298	744	1109
				(0·038)	(0·022)	(0·269)	(0·671)	
S–Sr	0·61	103	—	35	20	242	609	905
				(0·038)	(0·022)	(0·267)	(0·673)	
S–Ba	0·27	77	—	20	10	114	289	432
				(0·045)	(0·022)	(0·264)	(0·669)	
S–K–Mg	0·33	67	—	19	9	107	268	403
				(0·047)	(0·023)	(0·265)	(0·665)	
S–K–Ca	0·34	72	—	20	10	120	300	450
				(0·044)	(0·022)	(0·267)	(0·667)	
S–K–Sr	0·30	70	—	19	9	105	263	396
				(0·048)	(0·023)	(0·265)	(0·664)	
S–K–Ba	0·26	69	—	17	8	97	244	366
				(0·046)	(0·022)	(0·266)	(0·666)	
B–Li	1·18	139	—	56	34	420	1050	1559
				(0·036)	(0·022)	(0·269)	(0·673)	
B–Na	0·91	109	—	41	24	299	749	1113
				(0·037)	(0·021)	(0·269)	(0·673)	
B–K	0·44	72	—	21	12	139	348	520
				(0·041)	(0·022)	(0·268)	(0·669)	
P–Li	0·78	101	—	38	21	256	641	955
				(0·039)	(0·022)	(0·268)	(0·671)	
P–Na	1·08	117	—	45	27	342	860	1274
				(0·036)	(0·021)	(0·268)	(0·675)	
P–K	1·10	118	—	46	28	343	854	1271
				(0·036)	(0·022)	(0·270)	(0·672)	

by choosing appropriate glass composition, the intensity parameters (Ω_6) and in turn radiative properties (A, A_T and β_R) can be varied over a range. For example, A_T value for $^4S_{3/2}$ transition varies over a range of 297 s^{-1} (S–K)–12846 s^{-1} (CdBS).

5. Conclusions

The absorption band positions, integrated absorption cross-sections, Judd–Ofelt intensity parameters and in turn radiative properties for fluorescent levels of Er^{3+} : cadmium and alkali cadmium borate glasses are investigated. The trends in predicted radiative properties are similar to ternary sulphate glasses and differ from oxide glasses. Systematic decreasing or increasing trend in the magnitudes of Judd–Ofelt parameters are not clear when the glass compositions are modified by alkali or alkaline earths which suggests that further investigations are essential in this direction. The magnitudes of the A, A_T and β_R parameter values for ${}^4I_{13/2} \to {}^4I_{15/2}$ and ${}^4S_{3/2} \to {}^4I_J$ levels are mainly attributed to the magnitude of Ω_6 parameter.

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