REDDISH-ORANGE EMISSION FROM SAMARIUM DOPED PbO-AS$_2$O$_3$ GLASSES

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Abstract

The Sm$_2$O$_3$ doped lead arsenate glasses (40-x) PbO-60 As$_2$O$_3$-xSm$_2$O$_3$(x = 0.2,0.4,0.6,0.8 and 1.0 %) has been prepared by conventional melt quenching technique and is characterized through FT-IR and absorption and emission analysis. The FT-IR spectra analysis the structure and vibrational modes for these glasses. The optical absorption spectra exhibited several absorption transitions, Judd-Ofelt (JO) intensity parameters were obtained from the absorption spectrum. The emission spectra exhibited four transitions ^{4}G$_{5/2}$ → ^{6}H$_J$ (J = 5/2,7/2,9/2and11/2) ^{4}G$_{5/2}$ → ^{6}H$_{7/2}$ is responsible for reddish-orange emission and the calculated color coordinates for the present glasses fall well within the reddish-orange region of the CIE diagram.

Index Terms: PbO-As$_2$O$_3$ glasses; FT-IR; optical absorption; emission.

1.INTRODUCTION

Now a day's rare earth (RE) doped glasses play important role for the development of lasers, telecommunications, lighting, displays, photovoltaic devices and drug carriers. [1 - 4]. In generally, the optical and spectroscopic studies of RE ions are strongly dependent on host materials. One of the chosen host materials is oxide glasses which is chemically durability, thermally; optically transparent at the excitation and lasing wave lengths [5].Sm^{3+} doped laser materials are of interest in lasers for future generation nuclear fusion [6] Comparing to other rare-earth ions Sm^{3+} doped laser materials have many advantages and exhibit small emission efficiencies [7-8].The optical properties of RE ions with chemical Environment and this has been tested for Sm^{3+} in different hosts[9-10].Samarium has promised characteristics for spectral hole burning studies[11-12].

In the present investigations Sm^{3+} ions doped with PbO-As$_2$O$_3$ glasses.As$_2$O$_3$ is very strong network former, it's exhibiting high Raman scattering coefficient and low-loss materials for long-distance optical transmission [13-15].Several studies on As$_2$O$_3$ glasses mixed with alkali halides, rare earth oxides and some heavy metal oxides [16-20].Certain studies on As$_2$O$_3$ glasses mixed with different Semiconducting oxides viz; GeO$_2$, V$_2$O$_5$, SiO$_2$ etc are also available [21-23].An addition of PbO,As$_2$O$_3$ glasses are observed moisture resistant and low rates of crystallization. PbO is generally modifier but acts as dual role like modifier and glass former with PbO$_4$ structural units. If Pb-O is Ionic-glass modifier and Pb-O is Covalent-glass former. Certain studies on structural investigations reported earlier [24-29].

2. Experimental Methods
2.1 Glass Preparation

A series of PbO-As$_2$O$_3$ glasses doped with samarium ions (Sm^{3+}) were prepared by conventional melt quenching technique in the compositions of (40-x)PbO-60 As$_2$O$_3$- xSm$_2$O$_3$ (where x = 0.2, 0.4,0.6, 0.8 and 1.0%). The raw materials of lead oxide (PbO), Arsenic trioxide (As$_2$O$_3$) and Samarium oxide (Sm$_2$O$_3$) of appropriate amounts are mixed together and melted in silica crucible at a temperature of 600-650°c for 10 to 15 min until a bubble free liquid has been formed. The resultant melt was then poured in a brass mould and subsequently annealed from 200°c with a cooling rate 1 °c/min .Then the samples are finely polished to final dimensions 1 cm x 1 cm x 0.2 cm for the

measurements.Fig.1 represents photograph of PbO-As$_2$O$_3$ glasses doped with different concentrations of a Sm$_2$O$_3$.

2.2 Characterization

The refractive index of the glasses is measured by using abbe's refractometer and the density of the glasses calculated by means of Archimedes's principle. The Fourier transform infrared analysis is carried out using SHIMADZU-IRAffinity-1S FT-IR spectrophotometer with the resolution of 0.1cm^{-1} in the spectral range 400–4000 cm^{-1} using KBr pellets (300 mg) containing a pulverized sample (1.5 mg). The optical absorption (UV–VIS) spectra are recorded on JASCO, V-570 spectrophotometer from 200 to 2400 nm with spectral resolution of 0.1 nm.The excitation and emission were carried out by using FLS-980 Fluorescence spectrometer at room temperature by using xenon flash lamp as an excitation source having excited and emission wavelengths as 403.2 nm and 600 nm respectively.

3. Results
3.1 Physical parameters

From the measured values of density d and calculated average molecular weight $\overline{M}$, various physical parameters such as Samarium ion concentration N$_i$ and Samarium ion separation r$_i$ and other physical parameters also caliculated are presented in table 1.
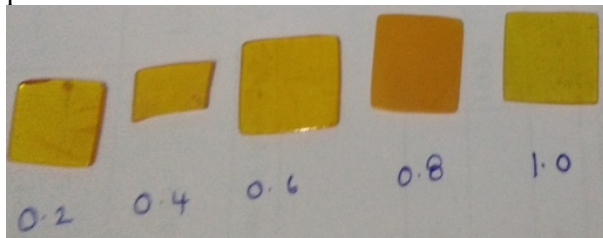

Fig. 1.Photograph of PbO-As$_2$O$_3$ glasses doped with different concentrations of Sm$_2$O$_3$

Density (d) and Molar Volume (V$_m$)
It has been observed that the concentration of Samarium increases the value of density decreased from 5.999 to 5.902. The molar volume increase from 34.71 to 35.45. The density decreases and the molar volume increase the compaction of structure of glass of increasing Samarium contents.

Polaron radius (r$_p$) and Field strength(F)
The variation of estimated values of r$_p$ and field strength for different concentrations is shown in

Table 1.From the Table 1 ,it is clear that the estimated values of r$_p$ decreases with increase of Sm$_2$O$_3$ content in the glass composition.This may be atributed to the enhanced compactness observed with Sm$_2$O$_3$ addition and due to the the decreases of the average rare-earth Oxygen distance.As a result of that,the Sm-O bond strength increases,producing stronger field strength around Sm^{3+} ions .

Molar electronic polarizability and metallization parameter

The relationship between the molar electronic polarizability (α$_m$) of the material and its molar refraction (R$_m$) is given by

$$\alpha_m = (3/4\pi N_A) \times R_m$$

Where N$_A$ is the Avogadro number. The α$_m$ values listed in Table 1, indicate the decrease of Rm values as well as the decrease in polarizabilites. For metals R$_m$/V$_m$ > 1, and non metals R$_m$/V$_m$ < 1 [33].

$$M = 1 - Rm/Vm$$

The magnitude of metallization values are decreased from 0.582 to 0.598 listed Table 1.Earlier reported the SiO$_2$ and B$_2$O$_3$ glasses containing fluorides, alkali metals alkali earth oxides small metallization factors ranging from to 0.5 to 0.7 [34] ,but my observations the values are also ranging 0.58 to 0.6.

3.2 FTIR spectral analysis

Fig.2.Shows the FT-IR transmittance spectrum of PbO-As$_2$O$_3$ doped with Sm$_2$O$_3$ glasses. The spectrum consists 5 bands are observed As$_2$O$_3$ exhibit four fundamental absorption bands: ν$_1$ -symmetric stretching vibrations (1050 cm^{-1}),ν$_2$ – symmetric bending vibrations (618 cm^{-1}),ν$_3$ –doubly degenerated stretching vibrations (795 cm^{-1}),ν$_4$ –doubly degenerated bending vibrations (505 cm^{-1}) [35], and other band (weak) is observed in the range 460-475 cm^{-1} due to PbO$_4$ units[36,37] in the spectra of all the glasses is observed. In the present paper the molar composition of Sm$_2$O$_3$ increases in steps from 0.2 to 1.0 mol%, all the bands are gradually increases.
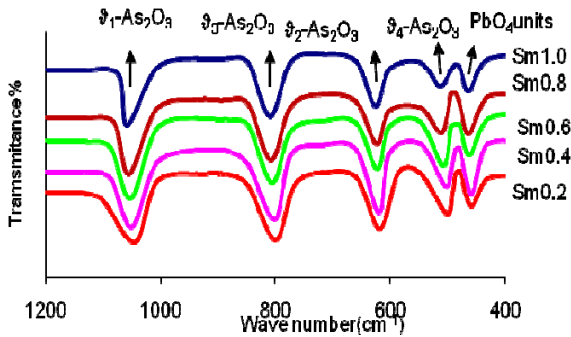
Fig.2. FT-IR spectra of PbO-As₂O₃:Sm₂O₃ glasses

3.3 Optical absorption spectra

The optical absorption spectra of PbO-As$_2$O$_3$:Sm$_2$O$_3$ glasses (Fig.3 (a) and (b)) measured at room temperature in the spectral wavelength range 300-1600 nm with spectral resolution of 0.1 nm, have exhibited 8 absorption bands corresponding to following transitions [38]: $^6H_{5/2}$ ⟶ $^4I_{13/2}$+$^4I_{11/2}$+$^4M_{17/2}$ (UV-visible region), $^6F_{11/2}$, $^6F_{9/2}$, $^6F_{7/2}$, $^6F_{5/2}$, $^6F_{3/2}$, $^6F_{1/2}$, $^6H_{15/2}$ (NIR region)

The pattern of the absorption spectra for all the glasses same. Samarium concentration is increases the intensity also increases but 0.6 Sm glass absorption band ($^6F_{11/2}$) is slightly decreases compare to 0.4 Sm.Genearally Sm^{3+} ions are exhibit several bands in the UV-region but we can found only one transition depending up on host materials.

From absorption edges, we have estimate the optical band gaps

(E$_o$) of these glasses by drawing Tauc plot (Fig-3(c)) between $(\alpha\hbar\omega)^{1/2}$ and $\hbar\omega$ as per the equation:

$$\alpha(\omega)\hbar\omega = C(\hbar\omega - E_0)^2$$

The optical band gap has been found to decline moderately with enlarge in the concentration Samarium in the glass matrix.The data related to optical absorption spectra of these glasses energy band gap(E$_0$) are presented in Table 1.

The importance of rare earth spectra earlier reported by Wybourne's book [39] .Conventional Judd-Ofelt (J-O theory) parameter has been calculated from the absorption spectra of Sm^{3+} ions. The intensity of the absorption bands can be estimated by using oscillator strength f$_{exp}$, which is calculated from the absorption spectra by using following equation

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

Where ε (ν) denotes the molar extinction coefficient at average energy ν in cm^{-1}. According to the f-f intensity model of the J-O theory [40],the calculated oscillator strength from initial state to an excited state for electric dipole transitions is determined by the J-O theory.

$$f(\psi J; \psi'J') = \frac{8\pi^2 mc\nu}{3h(2J+1)}\left[\frac{(n^2+2)^2}{9n}\right] X$$

$$\sum_{\lambda=2,4,6} \Omega_\lambda (\psi J \| U^\lambda \| \psi'J')^2 \text{ ------- (2)}$$

where m refer to the mass of the electron, c is the velocity of light in vacuum, h is the plank's constant, n is the refractive index of refraction of the glass, ν is the frequency of the transition.$(n^2+2)/9n$ is the refractive index. $\psi J \rightarrow \psi'J'$, Ω_λ (λ=2, 4 and 6) are the J-O intensity parameters and $\|U^\lambda\|$ are the doubly reduced matrix elements of the unit tensor operators are available in the literature [41] .Unit tensor operators of the rank λ=2, 4 and 6 which are evaluated from the intermediate coupling approximation for a transition $\psi J \rightarrow \psi'J'$. The experimental oscillator strengths of absorption bands of Sm^{3+} doped glass are determined from the known values of Sm^{3+} concentration, sample thickness, peak position and peak areas by using the equation 1. By applying least square fitting procedure to determine the J-O intensity parameters Ω_2, Ω_4 and Ω_6 using experimentally measured oscillator strength, rms deviation values are presented in Table 2 &3.

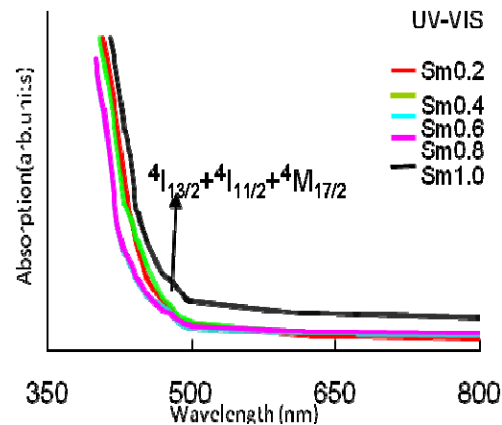**Fig.3 (a).Optical absorption spectra of PbO-As₂O₃:Sm₂O₃ glasses (UV-visible region)**
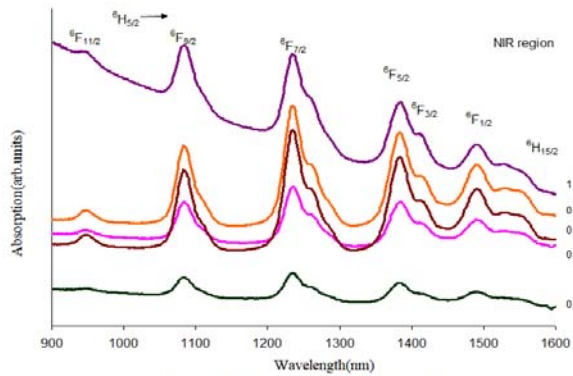
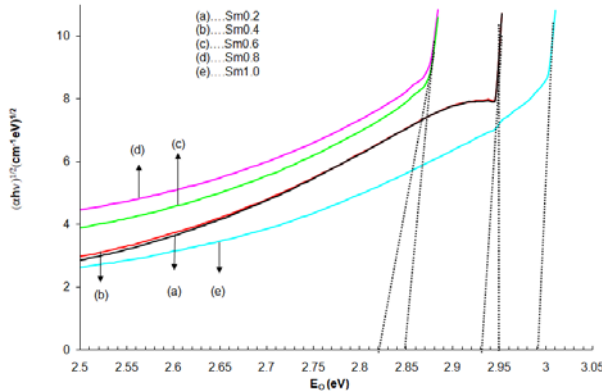Fig.3(b).Optical absorption spectra of PbO-As$_2$O$_3$: Sm$_2$O$_3$ glasses (NIR region)

Fig.3(c).Tauc plot of PbO-As$_2$O$_3$:Sm$_2$O$_3$ glasses

3.4 Excitation, emission Spectra and radiative properties

The Excitation wave length role plays important to the excitation spectra. The excitation spectrum of Sm0.2 glass by recording the emission of 600nm is shown in Fig 4 (a).It contains 12 excitation bands observed at 345,361,376,386,403,417,437,443,475,498 and 527nm $\longrightarrow$ correspondingtothe^{6}H$_{5/2}$to^{4}K$_{17/2}$,^{4}D$_{3/2}$,^{6}P$_{7/2}$,^{4}L$_{15/2}$,^{6}F$_{7/2}$,^{6}P$_{5/2}$,^{4}G$_{9/2}$,^{4}M$_{17/2}$,^{4}I$_{11/2}$,^{4}G$_{7/2}$ and ^{4}F$_{3/2}$ transitions respectively. The excitation band due to the ^{6}H$_{5/2}$ ^{4}I$_{11/2}$(475) transition is found to more intense. The emission spectra of Sm^{3+} doped PbO - As$_2$O$_3$ glasses recorded in the spectral region of 500-750 nm under 403.2 nm excitations presented in Fig 4 (b).The emission spectra exhibit 4 transitions ^{4}G$_{5/2}$ to ^{6}H$_J$ (J=5/2,7/2,9/2 and11/2).We can observed Sm$_2$O$_3$ concentration increases simultaneously the intensity also increased, transition from ^{4}G$_{5/2}$ to ^{6}H$_{7/2}$ (600nm) is the highest intensity and exhibits reddish orange .The ^{6}H$_{11/2}$ transition is very weak. The other two transitions (^{6}H$_{5/2}$, ^{6}H$_{9/2}$) show moderate intensities, these emissions are useful in medical diagnostics, color displays and high density optical storage. The partial energy level diagram shown in Fig4 (c).

.Non- radiative decay from (^{4}I$_{13/2}$+^{4}I$_{11/2}$+^{4}M$_{17/2}$) excited state to ^{4}G$_{5/2}$ Meta stable state. The larger energy gap between ^{4}G$_{5/2}$ level to next level ^{6}F$_{11/2}$ is 7117 cm^{-1}.The partial energy level diagram shown in Fig.4 (c). The spontaneous emission transition probability for transition from an initial state (ψJ) to a final state (ψ′J′) is given by [42]

$$A_R(\psi J; \psi'J') = \frac{64\pi^4 \nu^3}{3h(2J+1)} \left(\frac{n(n^2+2)^2}{9} S_{ed} + n^3 S_{md} \right) \qquad (3)$$

Where S$_{ed}$ and S$_{md}$ are electric and magnetic dipole line strengths .Electric dipole transitions are dominated comparing to magnetic dipole transitions, only we can calculate electric dipole transitions.

S$_{ed}$ can be expressed as

$$S_{ed} = \sum_{\lambda=2,4,6} \Omega_\lambda \left(\Psi J \left\| U^\lambda \right\| \Psi'J' \right)^2 \qquad (4)$$

Total radiative probability A$_T$ can be expressed as Summation of all possible radiative transition probabilities (A$_R$)

Stimulated emission cross-section (σ_P^E) can be expressed as

$$\sigma_P^E = \frac{\lambda_P^4 A_R}{8\pi c n^2 \Delta\lambda_{eff}} \qquad (5)$$

Where λ$_P$ is band intensity of corresponding peak position, A$_R$ s the radiation transition probability, Δλ$_{eff}$ is the effective line width, n is the refractive index, c velocity of light.

Branching ratio(β$_R$) can be expressed as

$$\beta_R = \frac{A_R}{A_T} \qquad (6)$$

Radiative lifetime(τ$_R$) can be expressed as

$$\tau_R = [A_T]^{-1} \qquad (7)$$

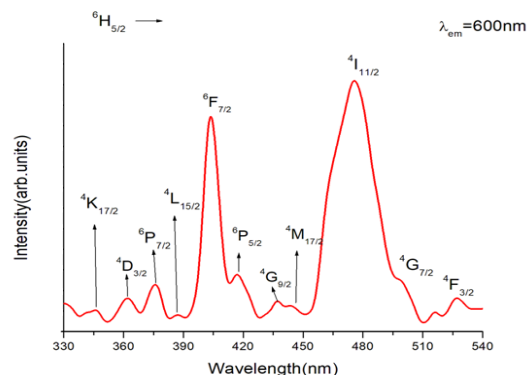Various radiative parameters are calculated in the present table 4.

Fig.4 (a). Excitation spectra of PbO-As$_2$O$_3$:Sm$_2$O$_3$ glass (0.2 mol %)

3.5 CIE color coordinates

The tunability of color emitted by the glass samples, the variation in the relative intensities of the emission bands has been analyzed in the CIE diagram [43].The diagram exhibits all the chromaticity visible to the human eye.Fig.5 shows the CIE (1931) chromaticity co-ordinates of Sm^{3+} doped $PbO\text{-}As_2O_3$ glasses under 403.2 nm excitations. The evaluated chromaticity coordinates (x,y) are (0.577,0.417), (0.580,0.409), (0.587,0.405), (0.593,0.396), (0.599,0.388) for Sm^{3+} doped $PbO\text{-}As2O3$ glasses (Sm0.2,Sm0.4,Sm0.6,Sm0.8,Sm1.0) respectively. These coordinates are very useful in determining the exact color of the samples. Fig.5 represents CIE diagram of Sm^{3+} doped $PbO\text{-}As_2O_3$ glasses.
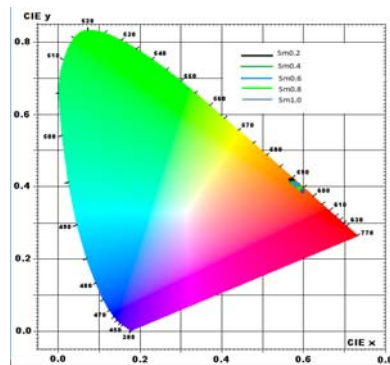

Fig.5. The CIE chromaticity diagram of $PbO\text{-}As_2O_3{:}Sm_2O_3$ glasses
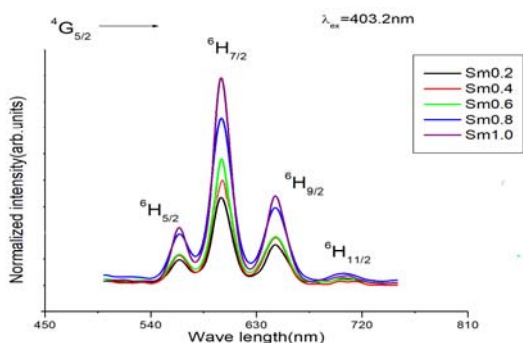
4. Discussion

The composition of $PbO\text{-}As_2O_3$; Sm_2O_3 glass system is an admixture of glass former,modifiers.As_2O_3 is one of the strong network former with corner sharing AsO_3 pyramidal units; normal bond lengths of As-O lie between 1.72 and 1.81 A^o and O-As-O and As-O-As band angles die in the range 90-103°, and 123-135° respectively[44].PbO is in generally modifier and enters the glass network by breaking up the As-O-As bands (normally the oxygen's of PbO break the local symmetry while Pb^{+2} ions occupy interstitial positions)and introduces coordinate defects known as dangling bands alloy with non-bridging oxygens; In this case Pb^{+2} octahedral coordinated.However,PbO may also participate in the glass network with PbO_4 structural units when lead ion is linked to four oxygens in a covalency bond configuration.

In the FT-IR spectra of these glasses the presence of meta center of v_3 vibrational band of ASO_3 units in the range of (800-809) also support this view. From X-ray diffraction studies(not shown), oxidation of As^{3+} to As^{5+} ions also appears possible. These As^{5+} ions occupy both tetrahedral and octahedral positions in the glass network; the normal bond length of As^{5+} - O is ~ 1.69 A^o [45, 46].The increase in intensity with the gradual shifting of the symmetric bending vibrational band (v_2) from 619-626 cm^{-1} with the introduction of Sm_2O_3 (up to 1 %) into the orderliness in the glass network. The vibrational bands located in the regions 1045-1059 cm^{-1} and 502-514. The presence of PbO_4 units in the present glass network can be established from the observation of vibrational bands between 460-465 cm^{-1}. In the optical absorption spectra, the absorption bands of

Fig.4 (b). Emission spectra of $PbO\text{-}As_2O_3$: Sm_2O_3 glasses

Fig.4 (c). Energy spectrum of $PbO\text{-}As_2O_3$: Sm_2O_3 glasses

Sm^{3+} ion can be classified into two groups: the first is the low-energy group which contains the transitions up to 10700 cm^{-1} (~ 935 nm) and the other is high-energy group containing the transitions in the range 17600-32000 cm^{-1} (~ 570-371 nm).We can observed in the visible region it is to be noted that several peaks at lower wave length disappear on addition of PbO [47, 48].Table -3 represents the comparison of Ω_λ values of Sm^{3+} ions in prepared glasses. Generally intensity parameter Ω_2 indicates the asymmetry and covalence of the Ln^{3+} sites. On the other hand,Ω_4 and Ω_6 values are related to the bulk property and rigidity of the samples. The Ω_λ values of prepared samples trend which is similar to TWSm10 [49] , NBNFS [50] , LKBPBG [51] , PbFPSm10 [52] and KNSZLSm10 [53] glasses. Compared to other glasses (1-5) the Ω_4 value is low, earlier reported [54] Ω_2 , Ω_4 and Ω_6 values are low compared to prepared glasses. Due to this reason the higher magnitude of Ω_4 suggests higher rigidity of the medium with higher covalence around the Sm^{3+} ion site. The photoluminescence spectrum consists of potential green, yellow and orange-reddish emission at 565, 600, 645 and 705 nm.The $^6H_{9/2}$ emission with the most intense line at 645 nm as well as the $^6H_{7/2}$ band at 600 nm is dominant in the spectrum. In the table-4, we can observed Sm_2O_3 concentration increases simultaneously β_R also increased, earlier reported (55) β_R values are above 0.5 due to this reason in the present investigations more intense reddish-orange emission is exhibited. The calculated color coordinates for the present glasses fall well within the reddish-orange region of the CIE diagram.

5. Conclusions

Sm^{3+} doped lead arsenate glasses have been prepared and characterized using FT-IR, absorption and emission spectra. The FT-IR spectrum revealed the structure and vibrational modes for lead arsenate glasses. The optical absorption spectra of these glasses exhibited several absorption transitions of Sm^{3+} ions in the visible and IR regions originating from $^6H_{5/2}$ ground state. Successfully explained J-O theory. Intense reddish-orange emission has been observed from PbO-As_2O_3:Sm_2O_3glasses.From the results of these investigations, it is concluded that the titled glasses are promising materials for the development of visible lasers, fluorescent display devices and optical amplifiers.

Table 1: various physical parameters of PbO-As_2O_3 glasses doped with Sm_2O_3

Glass	0.2	0.4	0.6	0.8	1.0
Density d (g/cm^3)	5.99	5.976	5.956	5.931	5.902
Avg.Mol. Weight ($\overline{M}$)	208.2	208.4	208.7	208.9	209.2
Conc.of Sm^{3+}ions N_i (10^{21}/cm^3)	3.47	6.90	10.31	13.67	16.98
Inter ionic distance r_i(A^o)	6.605	5.251	4.59	4.18	3.88
Polaron radius r_p(A^o)	2.66	2.11	1.85	1.68	1.56
Field strength F,($\times 10^{15}$ cm^{-2})	4.23	6.73	8.76	10.62	12.32
Refractive index(n)	1.777	1.765	1.758	1.741	1.731
Reflection loss	0.418	0.413	0.410	0.403	0.399
Molar volume (V_m)	34.71	34.88	35.0	35.23	35.4
Molar refraction(R_m)	14.50	14.40	14.36	14.20	14.14
Molar electronic polarizability(α_m)(A^o)^3	5.754	5.713	5.698	5.633	5.609
Metallization factor(M)	0.581	0.587	0.599	0.596	0.601
Optical band gap(eV)	2.95	2.93	2.85	2.82	2.99

Table 2: Oscillator strengths of various transitions of Sm^{3+} ion in PbO–As$_2$O$_3$ glasses.

Transition from $^6H_{5/2}$	Sm0.2		Sm0.4		Sm0.6		Sm0.8		Sm1.0	
	f_{exp} (x 10^{-6})	f_{cal} (x 10^{-6})	f_{exp} (x 10^{-6})	f_{cal} (x 10^{-6})	f_{exp} (x 10^{-6})	f_{cal} (x 10^{-6})	f_{exp} (x 10^{-6})	f_{cal} (x 10^{-6})	f_{exp} (x 10^{-6})	f_{cal} (x 10^{-6})
$^4I_{13/2}$ + $^4I_{11/2}$ + $^4M_{17/2}$	.8327	.0027	.8921	.0005	0.392	.0007	1.365	.0037	3.6662	.0066
$^6F_{11/2}$	.0014	-.0029	.0120	.0300	.0186	.0294	.5143	.1646	.6385	.2356
$^6F_{9/2}$	.0180	.0105	.1329	.1784	.1312	.1755	.9136	.9776	1.3416	1.4179
$^6F_{7/2}$	.1645	.1783	.2467	.2286	.2516	.2351	1.149	1.229	1.8088	1.9225
$^6F_{5/2}$	.3399	.3689	.0702	.0699	.0679	.0932	.4790	.4081	.9401	.8449
$^6F_{3/2}$	.2250	.2013	.0004	.0306	.0045	.0509	.3031	.4735	.3535	.6155
$^6F_{1/2}$	.0507	-.0002	.0403	.0016	.0424	.0015	1.123	.0086	.8488	.0123
$^6H_{15/2}$	.0165	.0380	.0160	-.0030	.0302	.0100	.4637	.3904	.4386	.3083
r.m.s. deviation	0.294		0.316		0.4157		0.639		1.340	

Table 3: J–O parameters, Sm^{3+} ion doped PbO–As$_2$O$_3$ glasses

Glass	Ω_2 (x 10^{-20}cm^2)	Ω_4(x 10^{-20}cm^2)	Ω_6(x 10^{-20}cm^2)	Trend
Sm0.2	.10191	.5975	- .247	$\Omega_4 > \Omega_2 > \Omega_6$
Sm0.4	0.1172	.1876	0.811	$\Omega_4 > \Omega_2 > \Omega_6$
Sm0.6	.14764	.176	.0264	$\Omega_4 > \Omega_2 > \Omega_6$
Sm0.8	1.0378	1.176	0.558	$\Omega_4 > \Omega_2 > \Omega_6$
Sm1.0	1.2903	1.436	0.816	$\Omega_4 > \Omega_2 > \Omega_6$
TWSm10(1)	2.01	4.38	1.56	$\Omega_4 > \Omega_2 > \Omega_6$
NBNFS(2)	2.15	3.95	1.89	$\Omega_4 > \Omega_2 > \Omega_6$
LKBPBG(3)	3.00	5.19	1.69	$\Omega_4 > \Omega_2 > \Omega_6$
PbFPSm10(4)	5.20	5.81	3.76	$\Omega_4 > \Omega_2 > \Omega_6$
KNSZLSm10(5)	8.30	8.80	3.43	$\Omega_4 > \Omega_2 > \Omega_6$
Tellurite(6)	0.006	0.339	0.243	$\Omega_4 > \Omega_6 > \Omega_2$

.

Table4: Various radiative properties of Sm^{3+} doped PbO–As$_2$O$_3$ glasses

Glass	Wavelength (nm)	Transition from $^4G_{5/2}$	S_{ed} (x 10^{-23})	A	A_T	β_R	σE_P (x 10^{-25})	τ_R (sec)
	565	$^6H_{5/2}$	4.474	12.63	78.81	0.16	44.77	0.0126
Sm0.2	600	$^6H_{7/2}$	14.57	35.14	78.81	0.44	2.80	0.0126
	643	$^6H_{9/2}$	4.57	10.45	78.81	0.13	19.82	0.0126
	705	$^6H_{11/2}$	2.64	4.58	78.81	0.05	5.33	0.0126
Sm0.4								
	565	$^6H_{5/2}$	2.86	9.35	42.9	0.21	20.462	0.023
	600	$^6H_{7/2}$	8.86	19.76	42.9	0.46	3.911	0.023
	642	$^6H_{9/2}$	2.32	6.34	42.9	0.14	121.5	0.023
	708	$^6H_{11/2}$	0.86	1.43	42.9	0.03	29.95	0.023
Sm0.6								
	565	$^6H_{5/2}$	2.47	7.26	25.74	0.28	8.92	0.0388
	600	$^6H_{7/2}$	3.60	12.6	25.74	0.49	0.79	0.0388
	645	$^6H_{9/2}$	1.49	3.51	25.74	0.13	6.37	0.0388
	705	$^6H_{11/2}$	0.98	1.77	25.74	0.06	1.99	0.0388
Sm0.8								
	565	$^6H_{5/2}$	12.13	32.50	126.3	0.25	183.09	0.0079
	600	$^6H_{7/2}$	13.61	63.15	126.3	0.499	33.64	0.0079
	645	$^6H_{9/2}$	15.70	34.18	126.3	0.27	21.35	0.0079
	705	$^6H_{11/2}$	4.37	7.23	126.3	0.05	43.85	0.0079
Sm1.0								
	565	$^6H_{5/2}$	20.84	59.66	234.1	0.25	18.43	0.0042
	600	$^6H_{7/2}$	31.48	128.3	234.1	0.54	20.92	0.0042
	644	$^6H_{9/2}$	18.44	42.49	234.1	0.18	46.65	0.0042
	706	$^6H_{11/2}$	8.39	14.81	234.1	0.16	37.19	0.0042

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