Impact of Dy$_2$O$_3$ Substitution on the Physical, Structural and Optical Properties of Lithium–Aluminium–Borate Glass System

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Abstract: In this study, a series of Li$_2$O-Al$_2$O$_3$-B$_2$O$_3$ glasses doped with various concentrations of Dy$_2$O$_3$ (where x = 0.0, 0.2, 0.4, 0.6, 0.8, and 1.0 mol%) were prepared by using a conventional melt-quenching technique. The structural, physical and optical properties of the glasses were examined by utilising a variety of techniques instance, X-ray diffraction (XRD), UV–Vis-NIR spectrometer, Fourier transform infrared (FTIR) and photoluminescence (PL). The XRD spectra demonstrate the amorphous phase of all glasses. Furthermore, the UV-vis-NIR spectrometers have registered optical absorption spectra a numbers of peaks which exist at 1703, 1271, 1095, 902, 841, 802, 669, 458, 393 and 352 nm congruous to the transitions from the ground of state ($^6$H$_{15/2}$) to different excited states, $^6$H$_{11/2}$, $^6$F$_{11/2}$ + $^6$H$_{9/2}$, $^6$F$_{9/2}$ + $^6$H$_{7/2}$, $^6$F$_{7/2}$, $^6$F$_{5/2}$, $^6$F$_{3/2}$, $^4$F$_{9/2}$, $^4$I$_{15/2}$, $^4$F$_{7/2}$ and $^6$P$_{7/2}$, respectively. The spectra of emission exhibit two strong emanation bands at 481 nm and 575 nm in the visible region, which correspond to the transitions $^4$F$_{9/2}$ → $^6$H$_{15/2}$ and $^4$F$_{9/2}$ → $^6$H$_{13/2}$. All prepared glass samples doped with Dy$_2$O$_3$ show an increase in the emission intensity with an increase in the concentration of Dy$^{3+}$. Based on the obtained results, the aforementioned glass samples may have possible applications, such as optical sensor and laser applications.

Keywords: borate glass; Dy$_2$O$_3$; UV-VIS-NIR; photoluminescence

1. Introduction

Borate glass has been acknowledge as a good host for various rare-earth (RE) oxides among the traditional glass formers due to their strong glass formulation when compared with other conventional systems such as phosphates, germanates, vanadates and tellurite glass [1]. In addition, the glassy system is available easily, inexpensive, simple to prepare and a good host for a variety of elements [2]. The structural, physical, and optical characteristics of the glasses are greatly influenced by the composition and synthesis conditions. Therefore, to accomplish high emission efficiency, most of the glass system is activated using suitable transitional metals and/or rare-earth elements.
The incorporation of rare-earth ions to the different glassy systems led to an improvement in the optical properties, such as refractive index, optical band gaps energy and laser amplification [3]. These improvements in optical properties for glassy systems drove them to be a potential candidate for lasers, solar concentrate systems, optical detectors, waveguides and telecommunications optical fibres [4].

Borate glasses have specific properties that make them beneficial for a wide technical application, but their chemical durability is relatively feeble, which limits their utility. Nevertheless, the addendum of oxides such as lithium oxide (Li₂O) and aluminium oxide (Al₂O₃) can enhance the chemical durability and physical properties. Moreover, adding metal oxides as modifiers to the host matrix raises the radiative parameters. Besides, glasses containing metals minimize phonon energy and lead to an increase in the luminescence quantum from excited rare-earth ion states [3]. Therefore, glasses doped with rare-earth elements may be used because of their ion emission efficiencies of 4f–4f and 4f–5d. The 5s and 5p orbits provide shielding effects to electrons determined by 4f, which leads to significant RE spectral absorption and emission lines [6,7]. Due to their unique characteristics, glass systems doped with rare-earth elements have been given considerable attention in recent decades.

Furthermore, between all the RE ions, trivalent dysprosium (Dy³⁺) ions have been extensively investigated for the production of or improvement in optical amplification systems in telecommunication. It is important to study the luminescence of Dy³⁺ ions in level ⁴F₉/₂ because it occurs in visible and NIR regions [8,9]. Usually, transitions of Dy³⁺ ion exhibit in yellow or blue regions of ⁴F₉/₂ → ⁶H₁₃/₂ (electric dipole) and ⁴F₉/₂ → ⁶H₁₅/₂ (magnetic dipole), respectively [10,11]. It has been established that the transition of ⁴F₉/₂ → ⁶H₁₃/₂ is hypersensitive, and therefore, its intensity depends heavily upon the existence of the host, while the intensity of transition of ⁴F₉/₂ → ⁶H₁₅/₂ is not quite sensitive to host conditions. Dy³⁺ has been acknowledged for its white light production, which is appropriate at an acceptable yellow to blue (Y/B) intensity ratio. Luminescent materials doped by Dy³⁺ ions are therefore commonly used both in glasses and phosphors to generate white light [5,6,10]. Moreover, Dy³⁺ ions have a various interesting characteristics such as high mechanical strength, high sensitivity and high thermal neutron absorption. They also can be utilized as the X-ray scintillators and as a yellow laser medium due to their intense yellow emission [12–14]. Unfortunately, there is limited information on the structure and physical properties of aluminium borate-bases doped with rare-earth ions, especially with Dy³⁺ ion. Hence, in this study, we seek to examine the impact of dysprosium oxide (Dy₂O₃) on the physical, structural and optical properties of 23Li₂O-(69.5 − x) B₂O₃-7.5Al₂O₃: xDy₂O₃ glass series (where x = 0, 0.2, 0.4, 0.6, 0.8 and 1 mol%).

2. Materials and Methods

2.1. Glass Preparation

The new glass formulation was prepared by using the conventional melt-quench technique. Various raw materials such as lithium oxide (Li₂O), aluminium oxide (Al₂O₃), boron oxide (B₂O₃) and trivalent dysprosium oxide (Dy₂O₃) were chosen at a specific ratio, as illustrated in Table 1. The chemical powders were weighed and mixed well for 60 min at 90 rpm. Then, the mixture was put in an alumina crucible and inserted in an electrical furnace for 30 min to be melted at 1000 °C to ensure complete melting. After that, the mixture was moved to another furnace for annealing at 400 °C for three hours. Then, the temperature of the furnace decreased progressively to reach the ambient temperature at a cooling rate of 10 °C per minute. Lastly, the samples were divided into two groups, where the first group was grinded to explore the characterisation, and the second group was buffed to investigate the optical of properties.
Table 1. Composition ratios for all studied glass samples.

| Glass Samples | Li$_2$O | Al$_2$O$_3$ | B$_2$O$_3$ | Dy$_2$O$_3$ |
|---------------|--------|------------|-----------|-----------|
| LABD-0.0      | 23     | 7.5        | 69.5      | 0.0       |
| LABD-0.2      | 23     | 7.5        | 69.3      | 0.2       |
| LABD-0.4      | 23     | 7.5        | 69.1      | 0.4       |
| LABD-0.6      | 23     | 7.5        | 68.9      | 0.6       |
| LABD-0.8      | 23     | 7.5        | 68.7      | 0.8       |
| LABD-1        | 23     | 7.5        | 68.5      | 1.0       |

2.2. Structural and Physical Parameters

The weight of the prepared glass samples was measured in air and distilled water using a sensitive microbalance based on the Archimedes principle. The density, $\rho$, of the samples was calculated by using the following equation

$$\rho = \left(\frac{W_A}{W_A - W_B}\right) \times \rho_B$$  \hspace{1cm} (1)

where $W_A$ and $W_B$ denote the sample weight in the air and distilled water, respectively, and $\rho_B$ is the density of distilled water, $\rho_B = 0.999 \text{gcm}^{-3}$. Molar volumes ($V_m$) for all glass samples were determined using the following equation

$$V_m = \left(\frac{M_{av}}{\rho}\right)(\text{cm}^3/\text{mol})$$  \hspace{1cm} (2)

where $M_{av}$ represents the average molecular weight. The average boron–boron separation $\langle d_{B-B}\rangle$ was calculated by applying the following formula

$$\langle d_{B-B}\rangle = \left[\frac{V^b_m}{N_A}\right]^{\frac{1}{3}}$$  \hspace{1cm} (3)

where $V^b_m$ refers to the volume of boron atoms per mole and is given by

$$V^b_m = V_m/2(1 - X_B)$$  \hspace{1cm} (4)

where $X_B$ is the mole fraction and $V_m$ is Molar volume for the glass samples [15]. The ion concentration can be acquired using the next expression

$$N = \left(\frac{X\% \times \rho \times N_A}{M_T}\right)(\text{ion/cm}^3)$$  \hspace{1cm} (5)

where $X\%$ is the mole percent of dopant, $N_A$ is the Avogadro number, and $M_T$ is the molecular weight. Based on the ion concentrations, it is also possible to compute three essential physical parameters, such as Polaron radius ($r_p$), inter-nuclear distance ($r_i$) and field strength

$$r_p(A^\circ) = \frac{1}{2}\left[\pi/6\lambda\right]^{\frac{1}{3}}$$  \hspace{1cm} (6)

$$r_i(A^\circ) = \left[\frac{V}{N}\right]^{\frac{1}{3}}$$  \hspace{1cm} (7)

$$F = \left(\frac{Z_m}{r_p^2}\right)$$  \hspace{1cm} (8)

where $Z_m$ is the atomic mass of the dopant [16,17].

The non-crystalline phases for the selected samples were observed using X-ray diffraction (XRD) system PANalytical X’pert PRO (PW3040/60 MPD, Philips, EA, The Netherlands). The system was combined with the software of diffraction analysis based on the 20 range from 10° to 80° with the steps 0.02°. Perkin Elmer Spectrum 100 (Waltham, MA, USA) instrument was utilized to obtain the
FTIR spectrum absorption for studied glasses with the size <63 µm in Attenuated-Total Reflectance (ATR) mode within wavenumber range of 400–4000 cm$^{-1}$.

2.3. Optical Properties

2.3.1. UV-Vis-NIR Absorption Spectra

UV-Vis spectrophotometer for reflective spectroscopy (RSA) (Lambda 35 Perkin Elmer, MA, USA) was used to estimate the absorption spectra of the glass samples within wavelength ranges of 200–2600 nm. Using absorption, the energy gap ($E_g$) can be obtained by applying the Mott and Davis relation

$$(ahv) = A(hv - E_g)^n / (hv)$$

where $a$ is coefficient of optical absorption, $A$ is a constant, $(hv)$ is the incident photon energy, and $E_g$ is the indirect permitted optical band gap energy. The direct $E_g$ value is obtained from the plot $(ahv)^{1/2}$, and $hv$ by extrapolating the linear-compatible regions to the value $(ahv)^{1/2} = 0$ [16]. Urbach energy ($E_u$) offers knowledge about glass disorder. This $E_u$ can be measured by using the relation [8]

$$a(v) = c. \exp (hv/E_u)$$

where $c$ is constant and $E_u$ is Urbach energy. The oscillator strength ($f_{exp}$) of glasses can be determined using the next equation

$$f_{exp} = 4.32 \times 10^{-9} \int \varepsilon(v) dv$$

where $\varepsilon(v)$ is the coefficient of molar the absorption of the each band at an energy of $v$(cm$^{-1}$) [17–19].

The refractive index ($n$) for the electronic polarization of ions and the local field of materials is among the most important optically dependent material parameters. The next relation can be used to define the refractive index ($n$)

$$\frac{(n^2 - 1)}{(n^2 + 2)} = 1 - \sqrt{\frac{E_g}{20}}$$

Reflective loss on the surface of the glass is determined by using the refractive index of the Fresnel formula

$$R_L = \left(\frac{(n - 1)}{(n + 1)}\right)^2$$

Using the Volf and Lorentz–Lorenz formula, the molar refraction ($R_m$) for all samples was measured [20,21]

$$R_m = \left(\frac{(n^2 - 1)}{(n^2 + 2)}\right) \cdot V_m$$

Molar refractivity ($R_M$) can be acquired using the following equation [22]

$$R_m = \left(\frac{(n^2 - 1)}{(n^2 + 2)}\right) \cdot \left(\frac{M}{\rho}\right)$$

The following relation can be used to estimate molar polarizability ($\alpha_m$) [23]

$$\alpha_m = \left(\frac{3}{4\pi N_a}\right) \frac{R_m}{R_M}$$
Metallisation criterion is the prediction of the metal or isolating behaviour of the condensed matter and is determined using the following relation [24]

\[ M = 1 - \left( \frac{R_m}{V_m} \right) \]  

(17)

The materials are considered metallic when \( R_m/V_m > 1 \), and they are considered insulating when \( R_m/V_m < 1 \). Further, the polarizability of electrons (\( \alpha_o \)) and optical basicity (\( \Lambda \)) linked electronegativity (\( \chi \)) can be obtained by [25]

\[ \chi = 0.2688E_g \]  

(18)

where (\( E_g \)) is optical band gap. The electronic polarizability is given by

\[ \alpha_o = -0.9\chi + 3.5 \]  

(19)

The relation between the electronic oxide polarizability and optical basicity is described by [26].

\[ \Lambda = 1.67(1 - \frac{1}{\alpha_{2-}}) \]  

(20)

The dielectric constant (\( \varepsilon \)) and optical dielectric constant can be calculated using the following formulae [8]. The dielectric constant has calculated using refractive index of the glass

\[ \varepsilon = n^2 \]  

(21)

where (\( n \)) is the refractive index. The optical dielectric constant of the glass calculated by the following relation

\[ \frac{p}{dt} = (\varepsilon - 1) = n^2 - 1 \]  

(22)

where \( \varepsilon \) is the dielectric constant.

### 2.3.2. Photoluminescence (PL) Spectrum

The LS55 Luminescence Spectrophotometer (Perkin Elmer, MA, USA) was used to determine photoluminescence between the wavelengths of 200 and 1300 nm. The luminescence signal was analysed based on excitation and emission methods using a Monk–Gillieson monochromator.

### 3. Results and Discussion

The pattern of the XRD for all the glass samples did not show any sharp diffraction or peaks, as shown in Figure 1, which confirms the amorphous nature for all the studied glass samples. Figure 2 shows the FTIR spectrum for lithium–aluminium–borate (LAB) glass doped with various Dy\(^{3+} \) ion concentrations. All infrared spectrums revealed several absorption bands, as listed in Table 2.

Density (\( \rho \)) is a key physical parameter for analysing the physical features of glass samples, as it indicates the relation between the masses and the volume within the glass system. Likewise, the molar volume (\( V_m \)) also correlates directly to the oxygen distribution in the glass structure. Figure 3 shows the relation between the density and molar volume of the glass upon adding the different concentrations of Dy\(_2\)O\(_3\).
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Figure 1. XRD pattern for all studied glasses.

Figure 2. FTIR of spectra for the various concentration of Dy$^{3+}$ doped in Li$_2$O–Al$_2$O$_3$–B$_2$O$_3$ glasses.
Table 2. FTIR assignment bands of Li2O–Al2O3–B2O3: Dy2O3 glasses.

| Positions of Band (cm⁻¹) for LAB Glasses with Diverse Dy³⁺ Ions Contents (mol%) | Band Assignments |
|---|---|
| 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 |
| 412.7, 526.5 | 416.6, 586.3 | 426.2, 540.06 | 433.9, 578.6 | 406.6, 588.3 | 406.9, 563.2 | Vibrations of Li⁺ ions [6]. |
| 692.4 | 696.3, 694.3 | 700.1 | 696.3 | 692.4 |
| 925.8, 1051.2 | 918.1, 1056.9 | 925.8, 1043.4 | 923.9, 1055.06 | 933.5, 1033.8 | 920.05, 1024.2 | B-O stretching of tetrahedral BO₄ bond [10]. |
| 1227.9, 1244.09, 1334.7 | 1244.09, 1332.8, 1375.2 | 1236.3, 1340.5, 1396.4 | 1246.02, 1328.9, 1377.1 | 1247.9, 1382.9 |
| 1375.2 | 1396.4, 1375.2 | 1390.6 | 1377.1 | 1382.9 |
| 1687.7 | 1687.7 | 1687.7, 1801.5 | 1687.7, 1870.9 | B-O-H bridge, OH bending vibration [28]. |
| 3269.3 | – | – | – | – | – | Stretching of OH groups or O-H (H₂O bond) [29]. |

Figure 3. Variation in density (ρ) and molar volume (Vm) concerning Dy₂O₃.

As illustrated in Table 3, the Vm of these glasses increases slightly with increasing Dy₂O₃ concentration up to 0.4 mol%, but the Vm values decrease gradually from 29.28 up to 29.17 cm³ with the addition of Dy₂O₃ up to 1 mol%. This enhancement in Vm value can be related to the decrement in glass compactness. Upon further addition of Dy₂O₃, the Vm values reduce gradually as a result of the increasing compactness of the glass system [27–29]. The replacement with Dy₂O₃ instead of B₂O₃ changes the ratio of boron to oxygen, creating BO₄ units that contribute to the compactness of the glass structure, thereby increasing the glass density. Furthermore, the molecular weight of Dy₂O₃ is higher than B₂O₃, meaning a significant increase in glass density [30].
Figure 4. Polaron radius, inter-nuclear distance and field strength as functions of Dy₂O₃ content of prepared glasses.

Table 3. Physical properties for all series of glasses.

| Physical Parameters * | Units | Doping (mol% Dy₂O₃) |
|------------------------|-------|---------------------|
|                        |       | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1    |
| Density                | (g.cm⁻³) | 2.144 | 2.162 | 2.182 | 2.210 | 2.238 | 2.260 |
| Molecular weight, Mᵣ | g      | 62.903 | 63.509 | 64.316 | 64.723 | 65.330 | 65.937 |
| Molar volume Vₑ       | (cm³/mol) | 29.339 | 29.375 | 29.384 | 29.286 | 29.191 | 29.175 |
| The volume of boron atoms per mole Vₚ   | (ions/cm³) | 16.031 | 11.959 | 11.886 | 11.058 | 11.656 | 11.576 |
| Ion concentration (N) ×10²⁰ | (ions/cm³) | 0.410 | 0.819 | 1.233 | 1.650 | 2.064 |
| Polaron radius         |        | 11.687 | 9.279 | 8.096 | 7.347 | 6.819 |
| Inter-nuclear distance (r₁) ×10⁻⁸ | (cm⁻²) | 29.0004 | 23.027 | 20.091 | 18.232 | 16.921 |
| Field strength (F) ×10⁻¹⁶ | (ions/µmol) | 2.144 | 2.162 | 2.182 | 2.210 | 2.238 | 2.260 |
| Average of boron-boron distance d₃₇,₇ | nm | 0.298 | 0.270 | 0.270 | 0.263 | 0.268 | 0.267 |

* With consideration of ± 0.01% error.

The calculated rₚ, r₁ and F values are listed in Table 3, and Figure 4 displays the behaviour of these parameters. The decrease in rₚ and r₁ with increased Dy₂O₃ is related to the decrease in the Dy–O distance, as a result of which the strength of the Dy–O bond increases, producing stronger field around Dy³⁺ ions [8]. Besides, the addition of Dy₂O₃ to the glass network led to overcrowding that decreased the average distance between the RE-oxygen. The significant increment in field strength values is, therefore, due to the appearance of strong linkages in the glass matrix between Dy³⁺ and B ions. [10]. It is noted from this table that the boron–boron separation d₄₇,₇ decreases with an increase in the Dy₂O₃ concentration due to the stretching force of the binds in the glass network.

Figure 5 displays the optical absorption spectrum for the Dy³⁺ doped lithium–aluminium–borate (LAB) glass samples within wavelengths in the range 300–1890 nm at room temperature. A spectrum identifies that the intensity of absorption raises with an addendum to Dy₂O₃ [29,31].
The energy band gap value can be obtained by using Equation (9) to plot the UV-absorption spectrum. Figure 6a and 6b show the indirect and direct bandgap, respectively. The variation between transition levels and their respective oscillator of strength for the glass samples are tabulated in Table 4. Noting that, the influence of Dy³⁺ ions on difference absorption bands led to their appropriate wavelengths, energies and oscillator strengths [34].

Figure 5 displays the optical absorption spectrum for the Dy³⁺ doped lithium–aluminium–borate (LAB) glass samples within wavelengths in the range 300–1890 nm at room temperature. A spectrum identification that the intensity of absorption raises with an addendum to Dy₂O₃ [29,31]. The spectra show ten inhomogeneous of absorption bands existing at the wavelengths 352, 393, 458, 669, 802, 841, 904, 1095, 1271 and 1703 nm due to the transitions of Dy³⁺ at the ground state (⁶H₁₅/₂)→⁶F9/2, ⁶H₇/₂) and (⁶H₁₁/₂), respectively [17]. Due to the strong absorption of LAB host glass, some of the absorption bands have disappeared in ultraviolet (UV) regions and are very sparse at 352 nm (⁶H₁₅/₂→⁶P₇/₂), 393 nm (⁶H₁₅/₂→⁴F₇/₂) and 456 nm (⁶H₁₅/₂→⁴I₁₅/₂), and also they have very low intensity [32]. Besides, the current samples showed a hypersensitive transition at 1270 nm (⁶H₁₅/₂→⁶H₁₁/₂) with high intensity and were subjected to the rule of selection |ΔS| = 0, |ΔL| ≤ 2, and |ΔJ| ≤ 2, where these transitions are more sensitive than others [33]. The variation between transition levels and their respective oscillator of strength for the glass samples are tabulated in Table 4. Noting that, the influence of Dy³⁺ ion on difference absorption bands led to their appropriate wavelengths, energies and oscillator strengths [34].

Table 4. The difference at transition levels and oscillator strengths.

| Absorption Transition | Wavelength (nm) | Energy (×10⁻³ cm⁻¹) | Oscillator Strength f_exp (×10⁻⁴) |
|-----------------------|-----------------|----------------------|----------------------------------|
| ⁶H₁₅/₂ → ⁶P₇/₂        | 352             | 29.321               | 0.451                            |
| ⁶H₁₅/₂ → ⁴F₇/₂        | 393             | 25.945               | 0.520                            |
| ⁶H₁₅/₂ → ⁴I₁₅/₂       | 458             | 22.234               | 0.696                            |
| ⁶H₁₅/₂ → ⁴F₉/₂        | 669             | 13.523               | 0.554                            |
| ⁶H₁₅/₂ → ⁶F₃/₂        | 802             | 12.644               | 0.615                            |
| ⁶H₁₅/₂ → ⁶F₅/₂        | 841             | 11.113               | 0.478                            |
| ⁶H₁₅/₂ → ⁶F₇/₂        | 902             | 10.145               | 1.305                            |
| ⁶H₁₅/₂ → ⁶F₉/₂ + ⁶H₇/₂| 1095            | 9.267                | 1.821                            |
| ⁶H₁₅/₂ → ⁶F₁₁/₂ + ⁶H₉/₂| 1271            | 7.834                | 3.218                            |
| ⁶H₁₅/₂ → ⁶H₁₁/₂       | 1703            | 3.533                | 3.046                            |

Figure 5 illustrate the optical energy band gaps for direct and indirect based on the curves of the UV-absorption spectrum. Figure 6a and 6b show the indirect and direct bandgap, respectively. The energy band gap value can be obtained by using Equation (9) to plot (αhv)² against photon energy (hv). Then, the linear extrapolating region of the curves extending to the X-axis gives the energy bandgap (Eₚ) reading. In the recent glass system, the values of the direct Eₚ exhibit from 3.650
to 3.706 eV, and the values of indirect ($E_g$) show a decrease from 3.189 to 2.556 eV with increasing dopant contents, as listed in Table 5. The declines in $E_g$ values may be due to structural changes due to the addition of Dy$^{3+}$ ions. The addition of Dy$_2$O$_3$ can contribute to an increase in electron localisation that increases donor centres in the glass matrix. This increment causes a decrease in $E_g$ values [35]. This is also because a new extrinsic band is formed by Dy$^{3+}$ on the grid between the boron and oxygen ions. As a consequence, there is an amount of possible reduction in (B–O–B) [36].

![Figure 6](image)

**Figure 6.** Bang gap energy: (a) Tauc’s plot for allowed direct transitions ($n = 2$); (b) Tauc’s plot for allowed indirect transitions ($n = 1/2$).

**Table 5.** Direct and indirect band gaps, Urbach energy ($E_u$) and cut-off wavelength ($\lambda_c$) of the samples studied.

| Sample  | $E_{\text{dir}}$ (eV) | $E_{\text{indir}}$ (eV) | $E_u$ (eV) | $\lambda_c$ [nm] |
|---------|----------------------|------------------------|------------|------------------|
| LABD-0.0| 3.580                | 3.189                  | 3.520      | 362.36           |
| LABD-0.2| 3.706                | 3.166                  | 3.337      | 368.83           |
| LABD-0.4| 3.566                | 2.919                  | 3.272      | 376.44           |
| LABD-0.6| 3.585                | 2.886                  | 3.075      | 385.81           |
| LABD-0.8| 3.473                | 2.7005                 | 3.352      | 394.15           |
| LABD-1  | 3.650                | 2.556                  | 3.058      | 401.81           |
Figure 7 indicates that the energy of Urbach decreases with changes in the Dy$_2$O$_3$ concentration. The reduction in the energy of Urbach is attributed to the creation of fewer defects, as reported [37]. Figure 8 and Table 6 show a slight gradual increase in refractive index values from 2.29 to 2.35 with increasing Dy$_2$O$_3$ concentration that can be attributed to the increase in electronic polarizability from 2.67 to 2.75 [17]. The sample has a higher refractive index, as it has a smaller bandgap value that reflects the compactness of the glass network structure. Meanwhile, the increment in molar refractivity and electronic polarisation values with increasing Dy$_2$O$_3$ concentration is indicated to form more non-bridging oxygen (NBOs) in the glass matrix [12].
Table 6. Optical properties of prepared glass samples.

| Measurement                          | 0.0       | 0.2       | 0.4       | 0.6       | 0.8       | 1.0       |
|--------------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| Refractive index (n)                 | 2.295     | 2.305     | 2.317     | 2.331     | 2.344     | 2.355     |
| Reflection loss (R_L)                | 0.154     | 0.155     | 0.157     | 0.159     | 0.161     | 0.163     |
| Molar refraction (R_m) (cm\(^{-3}\)) | 5.741     | 4.330     | 4.355     | 4.366     | 4.375     | 4.393     |
| Oxygen packing density (OPD)         | 86.57     | 86.46     | 86.44     | 86.72     | 87.01     | 87.81     |
| Optical basicity (\(\Lambda\))      | 1.240     | 1.248     | 1.257     | 1.268     | 1.277     | 1.285     |
| Optical electronegativity (\(\lambda\)) | 0.919     | 0.903     | 0.885     | 0.863     | 0.845     | 0.829     |
| Metallisation criterion (M)          | 0.412     | 0.410     | 0.407     | 0.403     | 0.400     | 0.397     |
| Molar refractivity (R_M) (cm\(^{-3}\)) | 17.227    | 17.324    | 17.420    | 17.467    | 17.505    | 17.576    |
| Molar polarizability (\(\alpha_m\)) \times 10\(^{-24}\) (cm\(^{-3}\)) | 2.275     | 1.716     | 1.716     | 1.730     | 1.734     | 1.741     |
| Dielectric constant (\(\varepsilon\)) | 5.267     | 5.313     | 5.368     | 5.433     | 5.494     | 5.546     |
| Optical dielectric constant          | 4.267     | 4.313     | 4.368     | 4.433     | 4.494     | 4.546     |
| Electron polarizability (\(\alpha_o\)) | 2.672     | 2.687     | 2.703     | 2.723     | 2.739     | 2.753     |

Table 6 presented the optical properties of the glass samples. It is observed that the molar refractivity (R_M), reflection loss (R_L) and refractive index (n) has a significant influence on the polarizability (\(\alpha_m\)) which demonstrates that the refractive index of the glasses does not solely depend on the density. It is known that the samples containing NBOs have great polarizability compared with samples containing bridging oxygen (BOs). The results presented here are in agreement with another work [38].

The theoretical optical basicity (\(\Lambda\)) is a calculation of oxygen’s capacity to contribute a negative charge load in glasses. To classify the covalent/ionic ratios of the glass, the theoretical optical basicity may be used, because the increment in (\(\Lambda\)) values indicate the declining covalence. Table 6 indicates that the values of \(\Lambda\) are within the range 1.240–1.285 and found to increase with increasing Dy\(_2\)O\(_3\) concentrations. Here, the increment in optical basicity values means the ability of oxide ions to transfer electrons in the cations surrounding them [7]. Figure 9 represents the decline in the metallization criterion with an increase in the Dy\(_2\)O\(_3\) concentration. The obtained values confirm the non-metallic nature of the current glass samples [8]. From Table 3, the results show that the refractivity R_M, \(\alpha_M\), \(\varepsilon\) and optical dielectric constant increase with increasing Dy\(_2\)O\(_3\), meaning an increase in NBOs inside the glass matrix.

![Figure 9. Variation in metallisation criterion with mol% Dy\(_2\)O\(_3\).](image-url)
The PL spectra for the current samples of various Dy$^{3+}$-doped compositions of (LAB) glass registered at room temperature in the wavelength region 420–720 nm below the excitation of the wavelength 375 nm are exhibited in Figure 10.

![Figure 10](image-url)  
**Figure 10.** Emission spectra of LAB glasses doped with different concentrations (in mol%) of Dy$^{3+}$ ions.

It was noticed that the emission peaks' intensity increased gradually as Dy$^{3+}$ concentrations increased from 0.2 mol% to 1 mol%. The bands obtained in this present work are in agreement with the previous investigations [39]. Five emission peaks were spotted, containing two comparatively intense emission bands at nearly 481 and 575 nm, respectively, for the transitions $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$ and $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$, and three considerably feeble bands at almost 458, 661 and 689 nm corresponding to the transitions $^4\text{I}_{15/2} \rightarrow ^6\text{H}_{15/2}$, $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{11/2}$ and $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{9/2}$, respectively [40]. These transitions are similar to other study, where the transition $^4\text{I}_{15/2}$ level excites the Dy$^{3+}$ ions at band 458 nm [12]. The excited Dy$^{3+}$ ions populate the $^4\text{F}_{9/2}$ meta-stable state during rapid of non-radiative decay process due to the small energy gap between $^4\text{I}_{15/2}$ and $^4\text{F}_{9/2}$ states [41]. The main higher band at 575 nm ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$) in the yellow range of the visible spectrum is a supersensitive transition following the selection rules ($\Delta J = \pm 2$ and $\Delta L = \pm 2$) [42].

In addition, the band at 481 nm ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{11/2}$), which is in the blue range, has low sensitivity to the host glass and is lower than the band at 575 nm that applies the selection rules ($\Delta J = \pm 3$). Therefore, the intensity of this transition is heavily impacted by the surrounding environment. Further to this, the weak intensity of emission bands appears at 661 nm ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{11/2}$) and 689 nm ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{9/2}$) is in the red range, which follows the selection rules ($\Delta J = \pm 1$) and ($\Delta J = 0$), $^6\text{F}_{11/2}$, respectively [33,43]. Spectroscopic and luminescence properties at 0.8 mol%-doped dysprosium ion are compared with other reported glass matrices and are found to be useful for yellow lighting applications in the visible spectral region. Those emissions, especially those at the visible light range, may increase the sensitivity of the composition and are apt to be used in several applications such as sensors and solar cells. Figure 11 illustrates a partial energy level diagram for the composition (LAB) of glass doped by several concentrations of Dy$^{3+}$ ions. At excitation 375 nm, the Dy$^{3+}$ ions were excited from the lower level of $^6\text{H}_{15/2}$ to higher-level $^6\text{P}_{7/2}$. After that, when the Dy$^{3+}$ ions were decayed non-radiatively to $^6\text{F}_{9/2}$ level, the Dy$^{3+}$ moved downward radiatively below the excitation of $^4\text{I}_{15/2}$. Prominent emission bands have
been identified: $^6\text{H}_{15/2}$ (blue), $^6\text{H}_{13/2}$ (yellow) and $^6\text{H}_{11/2}$$-^6\text{H}_{9/2}$ (red). The second part of this figure represents the absorption transition from the lower level ($^6\text{H}_{15/2}$) into the various energy levels: $^6\text{H}_{11/2}$, $^6\text{F}_{13/2}$ + $^6\text{H}_{9/2}$, $^6\text{H}_{7/2}$, $^6\text{F}_{5/2}$, $^4\text{F}_{9/2}$, $^6\text{F}_{3/2}$, $^4\text{I}_{15/2}$, $^4\text{F}_{7/2}$ and $^6\text{P}_{7/2}$. Hence the emission, absorption transitions, non-radiative, radiative energy transfer, cross-relaxation and ground state of the study samples are discussed.

4. Conclusions

In this study, new glass samples of the $23\text{Li}_2\text{O}$-$7.5\text{Al}_2\text{O}_3$(69.5 - $x$) $\text{B}_2\text{O}_3$: $x\text{Dy}_2\text{O}_3$ system were prepared using the melt-quenching technique. The amorphous nature of glass samples was confirmed by the XRD analysis. Notably, the density and optical basicity increased with the presence of $\text{BO}_4$ tetrahedral units and, due to the structural changes, led to the decline in the direct and indirect energy gaps. From PL results, five emission bands were observed around at 458, 481, 575, 561, and 689 nm, which are attributable to Dy$^{3+}$ transitions of $^4\text{I}_{15/2}$ $\rightarrow$ $^6\text{H}_{11/2}$, $^4\text{F}_{9/2}$ $\rightarrow$ $^6\text{H}_{13/2}$, $^4\text{F}_{9/2}$ $\rightarrow$ $^6\text{H}_{11/2}$ and $^4\text{F}_{9/2}$ $\rightarrow$ $^6\text{H}_{9/2}$, respectively. The 576 nm ($^4\text{F}_{9/2}$ $\rightarrow$ $^6\text{H}_{13/2}$) band is the largest. Hence, optical properties and other physical parameters, such as refractive index, density, molar volume, molar refractive, electrical polarisation and optical basicity, show a strong connexion with the speciation of dysprosium ions.

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References

1. Anjaiah, J.; Laxmikanth, C.; Veeraiah, N.; Nalluri, V. Spectroscopic properties and luminescence behaviour of europium doped lithium borate glasses. *Phys. B Condens. Matter* 2014, 454, 148–156. [CrossRef]

2. Alajerami, Y.S.M.; Hashim, S.; Ghoshal, S.K.; Saleh, M.A.; Kadni, T.; Saripan, M.I.; Saripand, K.; Alzimamie, Z.; Bradley, D.A. The Effect of TiO₂ and MgO on the Thermoluminescence Properties of a Lithium Potassium Borate Glass System. *J. Phys. Chem. Solids* 2013, 74, 1816–1822. [CrossRef]

3. Okasha, A.; Abdelghany, A.; Marzouk, S. The influence of Ba³⁺ and Sr²⁺ ions with the Dy³⁺ ions on the optical properties of lead borate glasses: Experimental and Judd–Ofelt comparative study. *J. Mater. Res. Technol.* 2020, 9, 59–66. [CrossRef]

4. Ramteke, D.D.; Gedam, R.S. Study of Li₂O–B₂O₃–Dy₂O₃ glasses by impedance spectroscopy. *Solid State Ion.* 2014, 258, 82–87. [CrossRef]

5. Damodaraiah, S.; Prasad, V.R.; Babu, S.; Ratnakaram, Y. Structural and luminescence properties of Dy³⁺ doped bismuth phosphate glasses for greenish yellow light applications. *Opt. Mater.* 2017, 67, 14–24. [CrossRef]

6. Pawar, P.; Munishwar, S.; Gautam, S.; Gedam, R. Physical, thermal, structural and optical properties of Dy³⁺ doped lithium aluminoborate glasses for bright W-LED. *J. Lumin.* 2017, 183, 79–88. [CrossRef]

7. Chimalawong, P.; Kirdsiri, K.; Kaewkhao, J.; Limsuwan, P. Investigation on the Physical and Optical Properties of Dy³⁺ Doped Sodium-Lime-Silicate Glasses. *Procedia Eng.* 2012, 32, 690–698. [CrossRef]

8. Yusof, N.N.; Ghoshal, S.K.; Omar, M.F. Physical, structural, optical and thermoluminescence behaviour of Dy₂O₃ doped sodium magnesium borosilicate glasses. *Results Phys.* 2019, 12, 827–839.

9. Anwar, A.; Zulfiqar, S.; Yousuf, M.A.; Ragab, S.A.; Khan, M.A.; Shakir, I.; Warsi, M.F. Impact of rare earth Dy³⁺ cations on the various parameters of nanocrystalline nickel spinel ferrite. *J. Mater. Res. Technol.* 2020, 9, 5313–5325. [CrossRef]

10. Mhareb, M.; Hashim, S.; Ghoshal, S.; Alajerami, Y.; Bqoor, M.J.; Hamdan, A.I.; Saleh, M.A.; Karim, M.K.A. Effect of Dy₂O₃ impurities on the physical, optical and thermoluminescence properties of lithium borate glass. *J. Lumin.* 2016, 177, 366–372. [CrossRef]

11. Mhareb, M.; Hashim, S.; Ghoshal, S.K.; Alajerami, Y.S.M.; Saleh, M.A.; Azizan, S.A.B.; Razak, N.A.B.; Karim, M.K.A. Influences of dysprosium and phosphorous oxides co-doping on thermoluminescence features and kinetic parameters of lithium magnesium borate glass. *J. Radioanal. Nucl. Chem.* 2015, 305, 469–477. [CrossRef]

12. Pawar, P.P.; Munishwar, S.R.; Gautam, S.; Gedam, R.S. Structural and photoluminescence properties of Dy³⁺ doped different modifier oxide-based lithium borate glasses. *J. Lumin.* 2012, 132, 2984–2991.

13. Zelati, A.; Amirabadizadeh, A.; Hosseini, A. A facile approach to synthesize dysprosium oxide nanoparticles. *Int. J. Ind. Chem.* 2014, 5, 69–75. [CrossRef]

14. Khan, I.; Rooh, G.; Rajaramakrishna, R.; Srisittiopokakun, N.; Kim, H.J.; Kaewkhao, J.; Ruangtaweep, Y. Photoluminescence Properties of Dy³⁺ Ion-Doped Li₂O-PbO-Gd₂O₃-SiO₂ Glasses for White Light Application. *Braz. J. Phys.* 2019, 49, 605–614. [CrossRef]

15. Mhareb, M.; Almessiere, M.; Sayyed, M.; Alajerami, Y. Physical, structural, optical and photons attenuation attributes of lithium-magnesium-borate glasses: Role of Tm₂O₃ doping. *Optik* 2019, 182, 821–831. [CrossRef]

16. Kamaruddin, W.; Rohani, M.; Sahar, M.; Liu, H.; Sang, Y. Synthesis and characterization of lithium niobium borate glasses containing neodymium. *J. Rare Earths* 2016, 34, 1199–1205. [CrossRef]

17. Ichoja, A.; Hashim, S.; Ghoshal, S.; Hashim, I.H.; Omar, R. Physical, structural and optical studies on magnesium borate glasses doped with dysprosium ion. *J. Rare Earths* 2018, 36, 1264–1271. [CrossRef]

18. Effendy, N.; Wahab, Z.A.; Aziz, S.A.; Matori, K.A.; Zaid, M.H.M.; Rashid, S.S.A.; Nuraidayani, E.; Abdul, W.Z.; Hj., A.A.S.; Amin, M.K.; et al. Characterization and optical properties of erbium oxide doped ZnO–SLS glass for potential optical and optoelectronic materials. * Mater. Express* 2017, 7, 59–65. [CrossRef]

19. Shaaban, K.; El-Maaref, A.; Abdelawwad, M.; Saddeek, Y.B.; Wilke, H.; Hillmer, H. Spectroscopic properties and Judd–Ofelt analysis of Dy³⁺ ions in molybdenum borosilicate glasses. *J. Lumin.* 2018, 196, 477–484. [CrossRef]

20. Babu, M.R.; Babu, A.M.; Moorthy, L.R. Structural and optical properties of Nd³⁺-doped lead borosilicate glasses for broadband laser amplification. *Int. J. Appl. Eng. Res.* 2018, 13, 7692–7700.
21. Bhatia, B.; Meena, S.L.; Parihar, V.; Poonia, M. Optical Basicity and Polarizability of Nd\textsuperscript{3+}-Doped Bismuth Borate Glasses. *New J. Glas. Ceram.* 2015, 5, 44–52. [CrossRef]

22. Gedam, R.; Ramteke, D. Influence of CeO\textsubscript{2} addition on the electrical and optical properties of lithium borate glasses. *J. Phys. Chem. Solids* 2013, 74, 1399–1402. [CrossRef]

23. Hasnimulyati, L.; Halimah, M.K.; Zakaria, A.; Halim, S.A.; Ishak, M.; Eevon, C. Structural and optical properties of Tm\textsubscript{2}O\textsubscript{3}-doped zinc borotellurite glass system. *J. Ovonic Res.* 2016, 12, 291–299. [CrossRef]

24. Kundu, V.; Dhiman, R.L.; Maan, A.S.; Goyal, D.R.; Garg, A.B.; Mittal, R.; Mukhopadhyay, R. Optical Properties of Alkaline Earth Ions Doped Bismuth Borate Glasses. *AIP Conf. Proc.* 2011, 1349, 545. [CrossRef]

25. Kaur, P.; Singh, K.; Kurudirek, M.; Thakur, S. Study of environment friendly bismuth incorporated lithium borate glass system for structural, gamma-ray and fast neutron shielding properties. *Spectrochim. Acta Part A Mol. Biomol. Spectrosc.* 2019, 223, 117309. [CrossRef]

26. Algradee, M.A.; Sultan, M.; Samir, O.M.; Alwany, A.E.B. Electronic polarizability, optical basicity and interaction parameter for Nd\textsubscript{3}O\textsubscript{3} doped lithium–zinc–phosphate glasses. *Appl. Phys. A Mate. Sci. Process.* 2017, 123, 524. [CrossRef]

27. Pawar, P.; Munishwar, S.R.; Gedam, R. Eu\textsubscript{2}O\textsubscript{3} doped bright orange-red luminescent lithium alumino-borate glasses for solid state lighting. *J. Lumin.* 2018, 200, 216–224. [CrossRef]

28. Deepa, A.V.; Priya, M.; Suresh, S. Influence of Samarium Oxide ions on structural and optical properties of borate glasses. *Sci. Res. Essays* 2016, 11, 57–63. [CrossRef]

29. Chandrasekhar, M.; Nagabhushana, H.; SudheerKumar, K.; Dhananjaya, K.; Sharma, S.; Kavyashree, D.; Shivakumara, C.; Nagabhushana, B. Comparison of structural and luminescence properties of Dy\textsubscript{2}O\textsubscript{3} nanoparticles synthesized by co-precipitation and green combustion routes. *Mater. Res. Bull.* 2014, 55, 237–245. [CrossRef]

30. Ramteke, D.; Ganvir, V.; Munishwar, S.R.; Gedam, R. Concentration Effect of Sm\textsuperscript{3+} Ions on Structural and Luminescence Properties of Lithium Borate Glasses. *Phys. Procedia* 2015, 76, 25–30. [CrossRef]

31. Pawar, P.; Munishwar, S.; Gedam, R. Intense white light luminescent Dy\textsuperscript{3+} doped lithium borate glasses for W-LED: A correlation between physical, thermal, structural and optical properties. *Solid State Sci.* 2017, 64, 41–50. [CrossRef]

32. Shamshad, L.; Rooh, G.; Kirdsiri, K.; Srisittipokakun, N.; Damdee, B.; Kim, H.; Kaewkhaok. J. Photoluminescence and white light generation behavior of lithium gadolinium silicoborate glasses. *J. Alloys Compd.* 2017, 695, 2347–2355. [CrossRef]

33. Deopa, N.; Rao, A. Photoluminescence and energy transfer studies of Dy\textsuperscript{3+} ions doped lithium lead alumino borate glasses for w-LED and laser applications. *J. Lumin.* 2017, 192, 832–841. [CrossRef]

34. Dawaud, R.S.E.S.; Hashim, S.; Alajerami, Y.; Mhareb, M.; Tamchek, N. Optical and structural properties of lithium sodium borate glasses doped dysprosium ions. *J. Mol. Struct.* 2014, 1075, 113–117. [CrossRef]

35. Forley, D.; Stroili, F.; Wang, T.; Kaltz, S.; Lanne, A.; Mavrikakis, M.; Kottke, A.; Wannemacher, R.W.; Mandrus, D.; Shank, L.R. Optical properties of Eu\textsuperscript{3+} doped lithium–zinc–germanate glasses. *J. Mol. Struct.* 2017, 1096, 211–216. [CrossRef]

36. Algradee, M.A.; Sultan, M.; Samir, O.M.; Alwany, A.E.B. Electronic polarizability, optical basicity and interaction parameter for Nd\textsubscript{3}O\textsubscript{3} doped lithium–zinc–phosphate glasses. *Appl. Phys. A Mate. Sci. Process.* 2017, 123, 524. [CrossRef]

37. Yusof, N.N.; Ghoshal, S.; Omar, M.F. Modified absorption attributes of neodymium doped magnesium-zinc-sulfophosphate glass. *Malays. J. Fundam. Appl. Sci.* 2017, 13, 258–262. [CrossRef]

38. Bulus, I.; Dalhatu, S.A.; Isah, M.; Hussin, R.; Soje, E.A. Structural and Luminescence Characterization of Lithium-Borosulfophosphate Glasses Containing Dysprosium Ions. *Sci. World J.* 2017, 12, 98–101. [CrossRef]

39. Rani, P.R.; Venkateswarlu, M.; Mahamuda, S.; Swapna, K.; Deopa, N.; Rao, A. Spectroscopic studies of Dy\textsuperscript{3+} ions doped barium lead alumino fluoro borate glasses. *J. Alloys Compd.* 2019, 787, 503–518. [CrossRef]

40. Babu, A.M.; Jamalaiah, B.; Kumar, J.S.; Sasikala, T.; Moorthy, L.R. Spectroscopic and photoluminescence properties of Dy\textsuperscript{3+}-doped lead tungsten tellurite glasses for laser materials. *J. Alloys Compd.* 2011, 509, 457–462. [CrossRef]
42. Shasmal, N.; Karmakar, B. White light-emitting Dy$^{3+}$-doped transparent chloroborosilicate glass: Synthesis and optical properties. *J. Asian Ceram. Soc.* 2018, 7, 42–52. [CrossRef]

43. Deopa, N.; Rao, A.; Gupta, M.; Prakash, G.V. Spectroscopic investigations of Nd$^{3+}$ doped Lithium Lead Alumino Borate glasses for 1.06 µm laser applications. *Opt. Mater.* 2018, 75, 127–134. [CrossRef]

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