Investigation of Structural, Physical, and Attenuation Parameters of Glass: \( \text{TeO}_2\text{-Bi}_2\text{O}_3\text{-B}_2\text{O}_3\text{-TiO}_2\text{-RE}_2\text{O}_3 \) (RE: La, Ce, Sm, Er, and Yb), and Applications Thereof

Nehal Elkhoshkhany 1,2, Samir Marzouk 3, Mohammed El-Sherbiny 2, Heba Ibrahim 2, Bozena Burtan-Gwizdala 4, Mohammed S. Alqahtani 5,6, Khalid I. Hussien 5,7,*, Manuela Reben 8,9 and El Sayed Yousef 9,10,*

1. Introduction

Rare earth (RE) elements, such as La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, and Yb have many multilateral applications in advanced technology [1,2]. Recently, glass doped with rare earth (RE) ions has attracted interest due to its utility in various applications in...
the development of opto-electronic devices such as planar waveguides, fluorescent display devices, optical fibers, visible lasers, optical detectors, and optical amplifiers [3]. Tellurite glass, especially, has good optical characteristics such as a high dielectric constant, high refractive index, wide optical transmission windows, good semiconducting properties [4], low melting point, and low phonon energy (∼ 700 cm\(^{-1}\)), as compared to borate glass which has high phonon energy and exists at a range of 1300–1500 cm\(^{-1}\) [4–6]. Glass based on TeO\(_2\) has a weak Te–O bond as compared to other composite glass; the former can easily be broken, which is useful for accommodating metal oxides and rare earth ions [7]. Combined B\(_2\)O\(_3\) and TeO\(_2\) (borotellurite) glass exhibits high thermal stability, low phonon energy, easy fabrication, and chemical durability [8]. Borotellurite glass is widely used in several applications, particularly in opto-acoustics, radiation shielding, and micro-electronics [8]. Glass that contains heavy metal oxides (HMO), such as Bi\(_2\)O\(_3\), has high nonlinear second/third-harmonic generation, exhibits high thermal expansion, high density, and IR transmission [8–10]. TiO\(_2\) incorporated into the glass matrix improves covalent bond formation and reinforces a continuous network consisting of TiO\(_6\) with an increase in the amount of bridging oxygen (BO) [10–13]. Moreover, TiO\(_2\) improves the properties of chemical resistance and thermal stability when added to tellurite glass. Nupur Gupta et al. [10] reported that the addition of both TiO\(_2\) and Bi\(_2\)O\(_3\) to borotellurite glass leads to a decrease in the optical energy gap due to the formation of nonbridging oxygen (NBO), and the glass transition temperature, \(T_g\), was increased. The addition of La\(_2\)O\(_3\) to tellurite glass enhances the stability of the glass against crystallization. Cerium-ion-doped glass holds several applications in biosensors, solid oxide fuel cells, dielectric materials, and blue luminescent optical systems [14]. Depending on the excitation wavelength, Sm\(_2\)O\(_3\)-doped glass displays and emits a strong orange-red luminescence in the visible range [15], associated with \(^4\text{G}_5/2, ^6\text{H}_9/2\) transition. Er\(_2\)O\(_3\)-doped glass is considered to be a candidate for use in the manufacturing of optical amplifiers (EDFAs) and in the field of optical communications [16]. Furthermore, several researchers [17–21] have investigated tellurium-based glass for possible uses in nuclear-radiation-shielding applications. The shielding effectiveness for tellurium-based glass has been studied, with the results showing that glass containing 60 Mol % of lead oxide and heavy oxide, and recording the highest density resulted in higher linear attenuation values and superior shielding material protection with perfect shielding efficiency. In the same trend, our research group [22] developed a computation tool (MiKE) for estimating and analyzing the shielding and optical parameters for different types of shielding materials. Therefore, the purpose of the present research was to study the physical parameters as well as the optical and attenuation properties of novel tellurite glass structures modified with various rare earths ions: La\(^{3+}\), Ce\(^{3+}\), Sm\(^{3+}\), Er\(^{3+}\), and Yb\(^{3+}\).

2. Experimental Section

The prepared glass (BBTTER) with a composition of 25B\(_2\)O\(_3\)–20Bi\(_2\)O\(_3\)–45TeO\(_2\)–7TiO\(_2\) (BBTT), modified by 3RE\(_2\)O\(_3\) in mol\%, where RE is La; Ce; Sm; Er; or Yb, was manufactured using the melt-quenching method. Chemical powders of TeO\(_2\), B\(_2\)O\(_3\), Bi\(_2\)O\(_3\), TiO\(_2\), and RE\(_2\)O\(_3\) (La\(_2\)O\(_3\), Ce\(_2\)O\(_3\), Sm\(_2\)O\(_3\), Er\(_2\)O\(_3\), and Yb\(_2\)O\(_3\)) were homogenized and melted at 930 °C for 30 min in an electric furnace. We used a platinum crucible while melting to obtain a homogeneous mixture, stirring the mixture several times. Then, each melt was put into a polished stainless-steel container and annealed at 300 °C. The prepared glass samples are coded as: BBTTLa, BBTTCe, BBTTSm, BBTTER, and BBTTYb, as shown in Table 1. Al\(_2\)O\(_3\) powder of 600 grade was used to polish the glass samples. The value density of the samples was determined according to Archimedes’ method. The powder X-ray diffraction pattern (XRD) was determined using a Philips PW (1140) diffractometer, and a copper target (K\(\alpha = 1.54\) Å) was used to study the amorphous properties of prepared glass. A double-beam UV–Visible spectrophotometer (JASCO Corp, v-570, Rel-00, Tokyo, Japan) was used to determine the optical absorption spectrum of the glass. The refractive index was determined with a prism coupler (Meticon Model 2010, Pennington, NJ, USA).
Structural characterization of the glass was carried out using FTIR absorbance spectra (Perkin-Elmer spectrometer). For the prepared glass, the half-value layer, both the linear and mass attenuation coefficients, as well as the mean free pass were measured using a NaI detector system (SPECTECH-NaI 1.5 PX 1.5/2.0 IV, S/N 010723-6), with various gamma sources (Am\textsuperscript{241}-5\textmu CI-59.5 keV, Cs\textsuperscript{137}-5\textmu CI-662 keV, Co\textsuperscript{60}-5\textmu CI-1170, and 1330 keV), which was connected to a computer and based on the multichannel analyzer. Figure 1 shows a collimated beam which was produced at the detector level using a variety of gamma sources (Am\textsuperscript{241}-5\textmu CI-59.5 keV, Cs\textsuperscript{137}-5\textmu CI-662 keV, Co\textsuperscript{60}-5\textmu CI-1170, and 1330 keV), according to the technique described in [4].

Table 1. Compositions and codes of glass systems (45TeO\textsubscript{2}–25B\textsubscript{2}O\textsubscript{3}–20Bi\textsubscript{2}O\textsubscript{3}–7TiO\textsubscript{2}–3RE\textsubscript{2}O\textsubscript{3}) in mol%.

| Sample Name | Glass Composition (mol%) | Sample Color |
|-------------|--------------------------|--------------|
|             | TeO\textsubscript{2} | B\textsubscript{2}O\textsubscript{3} | Bi\textsubscript{2}O\textsubscript{3} | TiO\textsubscript{2} | La\textsubscript{2}O\textsubscript{3} | Ce\textsubscript{2}O\textsubscript{3} | Sm\textsubscript{2}O\textsubscript{3} | Er\textsubscript{2}O\textsubscript{3} | Yb\textsubscript{2}O\textsubscript{3} |
| BBTTLa      | 45 | 25 | 20 | 7 | 3 | — | — | — | — |
| BBTTCe      | 45 | 25 | 20 | 7 | — | 3 | — | — | — |
| BBTTSm      | 45 | 25 | 20 | 7 | — | — | 3 | — | — |
| BBTTTe      | 45 | 25 | 20 | 7 | — | — | — | 3 | — |
| BBTTYb      | 45 | 25 | 20 | 7 | — | — | — | — | 3 |
3. Results and Discussion

3.1. XRD, Physical Parameters, and UV–VIS–NIR Spectra

The X-ray diffraction (XRD) patterns of the glass samples were measured to investigate the nature of the glass samples, as shown in Figure 2. The absence of any discrete or sharp diffraction peaks in these profiles and the existence of broad bands proves that all the prepared glass samples had an amorphous nature. The density value ($\rho$) was calculated using Equation (1) [23].

$$\rho = \left( \frac{W_a}{W_a - W_t} \right) \cdot \rho_t \left( \text{gm/cm}^3 \right)$$

(1)

The weight of the glass sample in air is $W_a$, whereas the weight of the glass immersed in reference liquid toluene is $W_t$, where $\rho_t = 0.864 \text{ g/cm}^3$. The calculated density value of the prepared glass increased from 5.67 g·cm$^{-3}$ to 6.32 g·cm$^{-3}$, which corresponded to BBTTLa and BBTTYb glass, respectively. The results are shown in Table 1.

Figure 1. Experimental setup used for measuring the shielding parameters of the prepared samples.

Figure 2. XRD profile of prepared glass.
The molecular weights, \( M_{\text{wt}} \), of rare earth compounds are ordered as follows: \( \text{La}_2\text{O}_3 < \text{Ce}_2\text{O}_3 < \text{Sm}_2\text{O}_3 < \text{Er}_2\text{O}_3 < \text{Yb}_2\text{O}_3 \), corresponding to 325.5, 328.24, 348.72, 382.52, and 394.08 g mol\(^{-1}\), respectively. Thus, the density increased in the same trend, which means that the highest value of density occurred with \( \text{Yb}_2\text{O}_3 \) incorporated into the glass matrix; here, the network of the glass is more compact. It is possible to determine the glass sample’s molecular volume \( (V_m) \) and its oxygen molar volume \( (V_o) \) using Equations (2) and (3), respectively. These strongly depend on the value of the densities of the glass samples, tabulated in Table 2.

\[
V_m = \frac{\sum x_i M_{\text{wt}i}}{\rho} \quad (2)
\]

where “M_{\text{wt}i}” is the molecular weight and “\( x_i \)” is the fraction ratio of each oxide. The oxygen molar volume, \( V_o \), can be estimated by the relationship as follow:

\[
V_o = \left( \frac{\sum x_i M_{\text{wt}i}}{\rho} \right) \left( \frac{1}{\sum x_i n_i} \right) \quad (3)
\]

where “\( n_i \)” is the number of oxygen atoms in each oxide [24]. The number of bonds per unit volume, \( n_b \), of the prepared glass and the average force constant \( (F) \), calculated from Equations (4) and (5), respectively [25,26].

\[
n_b = \frac{N_a}{V_m} \sum x_i n_i \quad (4)
\]

\[
F = \frac{\sum x_i n_i f_i}{\sum x_i n_f} \quad (5)
\]

| Sample Name | \( \rho \) (g/cm\(^3\)) ± 0.001 | \( V_m \) (cm\(^3\)/mol) ± 0.0056 | Oxygen Molar Volume, \( V_o \) (cm\(^3\)/mol) ± 0.2980 | \( n_b \times 10^{22} \) (m\(^{-3}\)) | \( F \) (Nm\(^{-1}\)) | OPD (mol/L) ± 0.078 |
|-------------|-------------------------------|---------------------------------|---------------------------------|----------------|----------------|----------------|
| BBTTLa      | 5.67                          | 35                              | 14.1                            | 6.5            | 301.21        | 71.1           |
| BBTTCe      | 6.083                         | 32.5                            | 13.1                            | 7.05           | 300.2         | 76.2           |
| BBTTSm      | 6.17                          | 32.13                           | 12.95                           | 7.08           | 301.79        | 77.1           |
| BBTTEr      | 6.21                          | 32.11                           | 12.94                           | 7.09           | 301.48        | 77.2           |
| BBTTYb      | 6.31                          | 31.63                           | 12.7                            | 7.14           | 303.04        | 78.4           |

The stretching force, \( f_i \), of the oxide, \( i \), can be measured using the following formula:

\[
\frac{1.7}{r_i^3} \quad (6)
\]

The molar volume, \( V_m \), decreased from 34.9 cm\(^3\)/mol to 31.6 cm\(^3\)/mol, which corresponded to BBTTLa and BBTTYb, respectively, and the glass structures became more compact due to a reduction in interatomic space or bond length between atoms \( (r_i) \). The value of \( V_o \) decreased from 14.1 to 12.7 cm\(^3\)/mol\(^{-1}\) by increasing both values of \( n_b \) from 6.5 to 7.14 \( \times 10^{22} \) m\(^{-3}\) and \( F \) from 301.21 to 303.04 Nm\(^{-1}\), when replacing the modified rare earth oxide \( \text{La}_2\text{O}_3 \) by \( \text{Yb}_2\text{O}_3 \). Furthermore, the decrease in \( V_o \) may indicate a decrement in the formation of NBO atoms reported here. The values of \( V_m \), \( V_o \), \( n_b \), and \( F \) of the prepared glass are shown in Table 2. Equation (7) was used to compute the oxygen packing density, OPD, [23]:

\[
\text{OPD} = 1000 \cdot C \cdot \left( \frac{\rho}{M} \right) \quad (7)
\]
where “C” is the number of oxygen atoms per formula unit. The increase in the value of OPD from 71.06258 mol/liter to 78.40199 mol/liter of BBTTLa and BBTTYb, respectively, was associated with increases in the nb, T, and Mwt values of rare earth oxides.

The optical absorption spectra of BBTTR glass are shown in Figure 3. The results on the absorption edge provide important information on the transitions of the band structure of amorphous materials [27]. The absorption bands of BBTTR glass were detected at 1512, 973, 800, 650, 550, 520, and 490 nm, which corresponded to the transitions from 4I15/2 to 4I13/2, 4I11/2, 4I9/2, 4I9/2, 4S3/2, 2H11/2, and 4F7/2, respectively.

The absorbance spectra of BBTTSm glass exhibited bands at 1620, 1551, 1485, 1379, 13/2, 411/2, 4F5/2, 6F7/2, 4F9/2, 6F11/2, 4I13/2, 4M15/2, 4P5/2, and 4F7/2, respectively. In addition, there was a strong absorption band transition of the level 2F7/2 to 2F5/2 of the Yb3+-ion-modified BBTTYb glass. The absorption coefficient, α(ν), of the fabricated glass was calculated using the absorbance spectra and the relationship shown below [28]:

\[
\alpha(\nu) = 2.303 \cdot A \cdot d^{-1}
\]

where A represents the absorbance and d is the glass sample’s thickness in cm.

In amorphous material, optical transitions that occur at the absorption edge can be divided into two mechanisms: firstly, direct transitions are where the momentum of the electron from the valance to conduction band is preserved; secondly, there are indirect transitions where it is necessary to cooperate with the absorb/release phonon [29]. Mott and Davis [29] suggested a relationship between photon energy (hv) and absorption coefficient (α) to determine the indirect optical band gap, Eopt, as shown in Equation (9).

\[
(\alpha \cdot h\nu) = B (h\nu - E_{\text{opt}})^r
\]

where B is a constant known as the band tailing parameter, r, which depends on the type of mechanism transition (r = 2) associated with the allowed indirect transitions [30]. A graph was plotted for (αhν)1/2 versus (hν) to determine the indirect optical band gap, Eopt, as shown in Figure 4. The calculated values of the indirect optical band gap, Eopt, can be obtained by the extrapolation of the linear range of the curve with a linear axis at (Y-axis = 0), which represents the photon energy (hν) [31] and the value of Eopt for the
prepared glass, as evaluated in Table 3. In the BBTTRE glass system, the formation of TeO$_4$ caused oxygen anions to be tightly bound to the host materials; thus, the $E_{\text{opt}}$ increased with a decrease in the number of NBO [31]. The value of $E_{\text{opt}}$ depends on the structure of the prepared glass TBBT modified by 3RE$_2$O$_3$ in mol%, where RE is La, Ce, Sm, Er, or Yb. From the results presented in Table 3, the values of $E_{\text{opt}}$ increase from 2.1 to 2.81 eV. The $E_{\text{opt}}$ value increased as a result of more bridging oxygen being present (BO) and the decrease in the number of NBO, as confirmed in the FTIR results of the prepared glass discussed here.

The value of the refractive index, $n$, molar polarizability, $\alpha_m$, molar refraction, $R_m$, oxide ion polarizability, ($\alpha_o^{-2}$), and the value of optical basicity, ($\Lambda$), are important parameters for the fabrication of optical devices, especially fiber optic and laser material. Therefore, we determine these parameters of the studied glass by using the subsequent equations [32]:

$$\alpha_m = \left( \frac{3}{4\pi N_A} \right) R_m$$  \hspace{1cm} (10)

$$R_m = \left( \frac{n^2 - 1}{n^2 + 2} \right) V_m$$  \hspace{1cm} (11)

$$\alpha_o^{-2} = \frac{V_m}{2.52} \left[ 1 - \sqrt{\frac{E_{\text{opt}}}{200}} - \sum p \alpha_i \right] q^{-1}$$  \hspace{1cm} (12)

$$\Lambda = 1.67 \left[ 1 - \frac{1}{\alpha_o^{-2}} \right]$$  \hspace{1cm} (13)

where $N_A$ is Avogadro’s number, $p$ is the cation number, and $q$ denotes the number of ions of oxygen. The values of $n$, $R_m$, $\alpha_m$, and $\Lambda$ depend on the polarizability of ions; the type of RE was La, Ce, Sm, Er, or Yb, and the prepared BBTT glass was modified with 3RE$_2$O$_3$ in mol%. The values of $n$, $R_m$, $\alpha_m$, and $\Lambda$ decreased when the host glass network BBTT was modified with regard to the free ion polarizability due to internal contact and the polarizability of oxide rare earth ions decreased. High oxide ion polarizability and optical basicity are also closely related to the superior optical characteristics of tellurite glass. Herein, rare earth oxides had an order of polarizability of cation, $\alpha_i$, of (La$_2$O$_3$ = 1.32 Å$^3$), (Ce$_2$O$_3$ = 1.28 Å$^3$), (Sm$_2$O$_3$ = 1.16 Å$^3$), (Er$_2$O$_3$ = 0.89 Å$^3$), and (Yb$_2$O$_3$ = 0.86 Å$^3$) [33]. Furthermore, the values of optical basicity, $\Lambda$, in TeO$_2$-based glass, i.e., $\Lambda_{\text{TeO}_4} = 0.99$, $\Lambda_{\text{TeO}_4^-} = 1.23$, and $\Lambda_{\text{TeO}_3^-} = 0.82$, were estimated by Dimitrov and Komatsu [33]. This demonstrated the polarizability of the TeO$_2$ unit to be substantially lower that of the TeO$_4$ unit, supporting the order of $\Lambda_{\text{TeO}_4^-} > \Lambda_{\text{TeO}_4} > \Lambda_{\text{TeO}_3^-}$. Hence, highly distorted TeO$_4$ tbp units with NBOs and different Te–O bond lengths should produce significant electrical polarizabilities. It is therefore of interest to clarify the fraction of TeO$_4$$^-$ units created in the order La$_2$O$_3$ > Ce$_2$O$_3$ > Sm$_2$O$_3$ > Er$_2$O$_3$ > Yb$_2$O$_3$ for modifying the BBTT glass matrix.

### Table 3. Optical energy gap, $E_{\text{opt}}$; refractive index, $n$; molar polarizability, $\alpha_m$; molar refraction, $R_m$; oxide ion polarizability, $\alpha_o^{-2}$; metallization, M; and optical basicity, $\Lambda$, of the prepared glass.

| Sample Name | $E_{\text{opt}}$ (eV) ±0.01 | $n$ ±0.0001 | $R_m$ (cm$^3$) ±0.0466 | $\alpha_m$ (Å$^3$) ±0.0182 | $\alpha_o^{-2}$ (Å$^3$) ±0.0065 | M ±0.0008 | $\Lambda$ ±0.0025 |
|-------------|-----------------|-------------|---------------------|-----------------|-----------------|---------|----------|
| BBTTLa | 1.71 | 2.69 | 23.6 | 9.35 | 3.22 | 0.324 | 1.15 |
| BBTTCe | 2.47 | 2.61 | 21.5 | 8.52 | 2.88 | 0.339 | 1.09 |
| BBTTSm | 2.57 | 2.49 | 20.4 | 8.1 | 2.71 | 0.365 | 1.05 |
| BBTTEr | 2.68 | 2.46 | 20.2 | 8.008 | 2.68 | 0.371 | 1.04 |
| BBTTYb | 2.8 | 2.45 | 19.77 | 7.84 | 2.61 | 0.375 | 1.03 |
The metallization criterion, $M$, for BBTTRE glass was estimated as follow:

$$M = 1 - \frac{R_m}{V_m}$$

(14)

The change in rare earth La$_2$O$_3$ → Ce$_2$O$_3$ → Sm$_2$O$_3$ → Er$_2$O$_3$ → Yb$_2$O$_3$ → La$_2$O$_3$ modified host matrix TBBT, causing a decrease in the width of the valance band and an increase in $M$, and consequently, an increase in the optical energy band gap. As shown in Table 3, the BBTTLa glass had the largest value of $M$ and the smallest value of $E_{\text{opt}}$. In contrast, the BBTTYb glass had the smallest value of $M$ and the highest value of $E_{\text{opt}}$.

### 3.2. Structural Categorization of Glass Using FTIR Spectra

The FTIR spectra of the investigated glass were measured; consequently, these were deconvoluted using Gaussian fitting into several Gaussian peaks marked as ($a - x$) bands, as shown Figure 5. Bands of 370–400 cm$^{-1}$ have been linked to the stretching vibration mode of Bi–O–Bi linkages [34]. The bands observed at around 430, 440, 458, 425, and 430 cm$^{-1}$ are attributable to La–O, Ce–O, Sm–O, Er–O, and Yb–O stretching vibrations, respectively [35,36]. Clearly visible peaks in the range of 463–480 cm$^{-1}$ can be attributed to the bridging anion modes of Bi–O–Bi vibrations in distorted BiO$_6$ octahedral units [37,38]. As a result of the combination of the corners of the TeO$_4$, TeO$_3$–1, and TeO$_3$ units, the bands 494–512 cm$^{-1}$ were aligned and matched with vibration connections Te–O–Te or O–Te–O [39–41]. The different IR peaks observed in the range of 500–800 cm$^{-1}$ in the investigated glass may be related to the anti-symmetrical and symmetrical vibrations of TeO$_2$ [41]. The peaks located in the range of 552–563 cm$^{-1}$ were attributable to Bi–O$^-$ bending vibration in BiO$_5$ octahedral units [42]. The vibration of a continuous TeO$_4$ trigonal bipyramid network was associated with bands detected in the 576–600 cm$^{-1}$ range (tbp). These indicated the glass network’s more compacted connections [43]. The bands between 616 and 623 cm$^{-1}$ were related to Ti–O bending vibrations [44]. The occurrence of Te–O$_{ax}$ vibrations in the

| Sample Name | Eopt (eV) | Rm (cm$^{-1}$) | Vm (cm$^{-1}$) | $\Lambda_{oh\nu}$ | $\Lambda_{oh\nu}$ |
|-------------|----------|---------------|---------------|------------------|------------------|
| BBTTLa      | 1.71     | 2.69          | 23.6          | 9.35             | 3.22             |
| BBTTCe      | 2.47     | 2.61          | 21.5          | 8.52             | 2.88             |
| BBTTYb      | 2.57     | 2.49          | 20.4          | 8.1              | 2.71             |
| BBTTTSm     | 2.8      | 2.45          | 19.77         | 7.84             | 2.61             |
| BBTTTEr     | 2.68     | 2.46          | 20.2          | 8.008            | 2.68             |

Figure 4. Relationship between $(\alpha h\nu)^{1/2}$ and $h\nu$ of the prepared glass.
TeO$_4$ tetrahedral units was linked to the development of the very strong band which occurred in the region of 648 to 654 cm$^{-1}$. The vibrations of BO in TeO$_3$/TeO$_3^{+1}$ units were responsible for the peaks between 671 and 674 cm$^{-1}$ that were seen in all glass samples. The B–O–B connections in the borate network’s mode of vibration were responsible for the bands positioned in the range of 692–695 cm$^{-1}$ [42]. The bands between 712 and 721 cm$^{-1}$ were attributable to the NBO stretching modes present in TeO$_3$ units [43]. The TeO$_3$ trigonal pyramid (tp) and (TeO$_{3+1}$) polyhedral units (Te$_{eq}$–O)$_{as}$ and (Te$_{eq}$–O)$_{S}$ vibrational modes were responsible for the bands in the 759–772 cm$^{-1}$ range [42,43]. The bending vibrations of BO$_4$ at 600 to 800 cm$^{-1}$ and the B–O bond stretching vibrations of BO$_4$ tetrahedral units are responsible for the bands that developed between 800 and 1200 cm$^{-1}$.

Figure 5. Deconvoluted FTIR spectra of the prepared glass.
Figure 5. Deconvoluted FTIR spectra of the prepared glass.

The IR in the regions between 1200 and 1600 cm\(^{-1}\) were attributable to vibrations of B–O bonds from BO\(_3\) trigonal units [39]. Absorption from 912 to 925 cm\(^{-1}\) could be related to the stretching vibrations of B–O bond in BO\(_4\) units from diborate groups [44,45]. The peaks observed in the region of 990 to 1001 cm\(^{-1}\) may be attributable to the stretching vibrations of B–O–Bi linkages [37,38]. The IR peaks observed in the ranges of 1062–1067 cm\(^{-1}\) may be due to the stretching vibrations of B–O bonds in BO\(_4\) units from tri-, tetra-, and penta-borate groups [46]. The two IR peaks in the region of 1118 to 1120 cm\(^{-1}\) and 1162 to 1168 cm\(^{-1}\) in our investigated samples were attributable to TiO\(_4\) tetrahedral units [47]. Other IR peaks in the spectral ranges of 1241–1248 cm\(^{-1}\) were associated with the presence of asymmetrical stretching vibrations of B–O bonds in BO\(_3\) triangular units from pyroborate groups [47]. The peaks which appeared in the range of 1280–1285 cm\(^{-1}\) were related to the B–O asymmetrical stretching vibration of (BO\(_3\))\(^{-3}\) units in meta- and ortho-borate groups [45]. The next absorption bands in the spectral ranges of 1348–1349 cm\(^{-1}\) were attributable to symmetrical stretching vibrations of B–O bonds in triangular BO\(_3\) units from meta-, pyro-, and ortho-borate groups [47,48]. The IR peak at 1375 cm\(^{-1}\) in all glass samples may have been due to the asymmetrical stretching vibrations of B–O bonds in triangular BO\(_3\) units [40]. The IR peaks in the ranges of 1401–1404 cm\(^{-1}\) can be attributed to the asymmetrical stretching vibrations of B–O triangles with BO\(_3\), B\(_2\)O\(_4\), and stretching vibrations of borate triangles with NBO in various borate groups. The stretching vibrations of the B–O bonds in BO\(_3\) units obtained from different forms of borate groups were responsible for the bands seen between 1428 and 1430 cm\(^{-1}\) [40]. The peak at 1461 cm\(^{-1}\) may have been the result of three NBO oxygens in B–O–B links stretching in an anti-symmetrical manner [46]. All the IR bands in Table 4 were attributed to deconvolution FTIR spectra, as shown in Figure 5. Additionally, the ratio of TeO\(_4\) (tbp) to TeO\(_3\) (tp) conversion was determined using the FTIR spectra. The ratio values of TeO\(_4\)/TeO\(_3\) were 0.473, 0.504, 0.51, 0.52, and 0.53, corresponding to BBTTLa, BBTTCe, BBTTSm, BBTTEr, and BBTTYb, respectively. The ratio of transferring BO\(_4\) into BO\(_3\) was also determined from the deconvoluted FTIR spectra.
Values of the ratio BO\textsubscript{4}/BO\textsubscript{3} were 0.415, 0.5, 0.51, 0.52, and 0.53, which corresponded to BBTTLa, BBTTCe, BBTTSm, BBTTTe, and BBTTYb, respectively. The increases in the ratios of TeO\textsubscript{4}/TeO\textsubscript{3} and BO\textsubscript{4}/BO\textsubscript{3} show that the glass became more resistant as a result of the formation of additional bridging oxygens (BOs). Thus, the formation of BO sites with increased atomic numbers of rare earth elements resulted in a strictly dense glass structure that confirmed the increment in the \( \rho \) and decrement of \( V_m \) values for BBTTRE in the order similar to that La\textsubscript{2}O\textsubscript{3} \( \rightarrow \) Ce\textsubscript{2}O\textsubscript{3} \( \rightarrow \) Sm\textsubscript{2}O\textsubscript{3} \( \rightarrow \) Er\textsubscript{2}O\textsubscript{3} \( \rightarrow \) Yb\textsubscript{2}O\textsubscript{3} \( \rightarrow \) La\textsubscript{2}O\textsubscript{3} glass samples, which was consistent with the parameter changes.

Table 4. The location of FTIR absorption bands corresponding to the structural bonds of the prepared glass samples.

| Symbol | IR Bands Wavenumber (cm\textsuperscript{-1}) | Assignments |
|--------|---------------------------------------------|--------------|
| a      | 370–400                                     | Stretching mode of vibration of Bi–O–Bi linkages |
| b      | 430, 440, 458, 425, 430                   | Stretching vibration of La–O, Ce–O, Sm–O, Er–O, Yb–O |
| c      | 463–480                                     | Bi–O–Bi vibration in distorted BiO\textsubscript{6} octahedral units |
| d      | 494–512                                     | Symmetrical stretching or bending vibrations of Te–O–Te or O–Te–O linkages |
| e      | 552–563                                     | Bending vibration of Bi–O\textsuperscript{−} in BiO\textsubscript{6} units |
| f      | 576–600                                     | Vibration of the continuous network consisting of TeO\textsubscript{4} tbp |
| g      | 616–623                                     | Ti–O bending vibration |
| h      | 648–654                                     | Symmetrical stretching vibration of Te–O\textsubscript{ax} in TeO\textsubscript{4} tetrahedral units |
| i      | 671–674                                     | Stretching vibrations tellurium with BO of TeO\textsubscript{3}/TeO\textsubscript{3+1} units |
| j      | 692–695                                     | Bending vibrations of B–O–B linkages in the borate network |
| k      | 712–721                                     | Stretching modes of NBO found on TeO\textsubscript{3} and TeO\textsubscript{3+1} units |
| l      | 759–772                                     | Symmetrical and asymmetrical vibration of (Te\textsubscript{eq}–O) in TeO\textsubscript{3}–1 polyhedra or trigonal pyramid TeO\textsubscript{3} (tp) units |
| m      | 912–925                                     | Stretching vibrations of B–O bond in BO\textsubscript{4} units from diborate groups |
| n      | 990–1001                                     | Stretching vibrations of B–O–B linkages |
| o      | (1023–1028), (1062–1067)                   | Stretching vibrations of B–O bond in BO\textsubscript{4} units from tri-, tetra- and penta-borate groups |
| p      | (1118–1120), (1162–1168)                   | TiO\textsubscript{4} |
| s      | (1247–1248), (1280–1285)                   | Asymmetric stretching vibrations of B–O bond in BO\textsubscript{3} triangular units from meta-, pyro-, and ortho-borate groups |
| t      | (1317–1321), (1348–1349)                   | Symmetrical stretching vibrations of B–O bond in BO\textsubscript{3} triangular units from meta-, pyro-, and ortho-borate groups |
| u      | 1375                                        | Asymmetrical stretching vibrations of B–O bond in BO\textsubscript{3} triangular units |
| v      | 1401–1404                                   | Asymmetrical stretching vibrations of B–O triangle with BO\textsubscript{3}, B\textsubscript{2}O\textsuperscript{−} and stretching vibration of borate triangle with (NBO) in various borate groups |
| w      | 1428–1430                                   | Stretching vibration of B–O bond in BO\textsubscript{3} units from varied types of borate groups |
| x      | 1461                                        | Anti-symmetric stretching vibrations with 3 NBO of B–O–B linkages |
3.3. Attenuation Parameters

The total mass attenuation coefficient, $\mu_m = \frac{\ln \frac{I_0}{I}}{d}$, and the linear attenuation coefficient, $\mu = \frac{\ln \frac{I_0}{I}}{d}$, are calculated using the ratio between the intensities of the measured incident, $I_0$, and the transmission radiation, $I$; $d$ is the thickness of the shielding material. $HVL = 0.693 \frac{\mu}{\rho}$, and the MFP parameter was calculated as $MFP = \frac{1}{\mu}$. Figure 6 shows the calculated linear attenuation coefficient (LAC) of the prepared glass for different energies (59.5, 622, 1170, and 1330 keV) compared with commercially available glass shielding materials, namely, RS360 and RS 520. For instance, the LAC value for BBTTYb glass exhibited the best shielding properties at the energies of 622, 1170, and 1330 keV at 59.5 keV, as compared with RS 360 and RS520 glass. Furthermore, the prepared glass (BBTTER) with a composition of $25B_2O_3–20Bi_2O_3–45TeO_2–7TiO_2$ (BBTT) modified by $3RE_2O_3$ in mol%, where RE was La, Ce, Sm, Er, or Yb, was better than that reported in other glass systems modified with rare earth elements, such as $39B_2O_3–30PB0–20MO–10Bi_2O_3–1Eu_2O_3$ (where M is K, Na, Ca, Sr, or Ba) [49], $B_2O_3–CaO–TeO_2–ZnO–ZnF_2–Sm_2O_3$ [50], and $B_2O_3–SrCO_3–Nb_2O_3–BaCO_3–Dy_2O_3$ [51]. Tables 5 and 6 present the measured mass attenuation coefficients (MACs) of the prepared samples in comparison with the calculated theoretical values using the MIKE and WinXcom software. The HVL parameter signifies the material thickness that reduces the intensity of radiation by half. Herein, the values for HVL and MFP of the prepared glass were lower than that reported for commercial materials, such as window glass, serpentine, concrete, SCHOOT glass RS253, hematite serpentine, Ilmenite, and SCHOOT glass RS323 [52–54]. Figure 7 shows the measured values of MAC, LAC, HVL, and MFP for the BBTTER glass at 59.5, 622, 1170, and 1330 keV, compared with the theoretical values calculated using MIKE software. The results showed good agreement between the measured mass attenuation coefficients and calculated values using MIKE software. Hence, the experimental attenuation results for the investigated prepared glass showed superior radiation shielding performance. Finally, we can estimate that the shielding parameters increased with the increasing ratios of $TeO_4/TeO_3$ and $BO_4/BO_3$ with bridging oxygens (BOs) of oxide glass, representing a candidate for the fabrication of superior shielding material.

Table 5. The measured mass attenuation coefficients of BBTTLa, BBTTCe, and BBTTSm samples in comparison with the values calculated using MIKE software and theoretical estimated values (WinXcom).

| Energy (keV) | BBTTLa | BBTTCe | BBTTSm |
|-------------|--------|--------|--------|
|             | Exp    | WinXCom | MIKE   | Exp    | WinXCom | MIKE   | Exp    | WinXCom | MIKE   |
| 59.5        | 4.528  | 4.717  | 4.7924 | 4.6070 | 4.741   | 4.9056 | 4.654  | 4.831   | 4.9056 |
| 662         | 0.094  | 0.090  | 0.0912 | 0.0989 | 0.091   | 0.0913 | 0.0841 | 0.0907  | 0.0914 |
| 1170        | 0.052  | 0.057  | 0.0580 | 0.0521 | 0.058   | 0.0580 | 0.0522 | 0.0579  | 0.0580 |
| 1330        | 0.046  | 0.053  | 0.0534 | 0.0463 | 0.053   | 0.0534 | 0.0464 | 0.0534  | 0.0535 |
Table 6. The measured mass attenuation coefficients of BBTTEr and BBTTYb samples in comparison with the values calculated using MIKE software and theoretical estimated values (WinXcom).

| Energy (keV) | BBTTEr | WinXCom | MIKE | BBTTYb | WinXCom | MIKE |
|-------------|--------|---------|------|--------|---------|------|
| 59.5        | 4.8245 | 4.988   | 5.0682 | 4.3090 | 4.4710 | 4.5282 |
| 662         | 0.0844 | 0.091   | 0.0917 | 0.0845 | 0.0912 | 0.0918 |
| 1170        | 0.0524 | 0.058   | 0.0581 | 0.0526 | 0.0580 | 0.0581 |
| 1330        | 0.0467 | 0.053   | 0.0535 | 0.0468 | 0.0535 | 0.0535 |

Figure 6. The calculated LAC for the glass samples compared with standard glass materials at energies: (A) 59.5; (B) 622; (C) 1170; and (D) 1330 keV.
Figure 7. The measured and theoretical shielding parameters for the BBTTEr glass system at different photon energies (59.5, 622, 1170, and 1330 keV): (A) MAC; (B) LAC; (C) HVL; and (D) MFP.

4. Conclusions

Incorporating the rare earth ions La$^{+3}$, Ce$^{+3}$, Sm$^{+3}$, Er$^{+3}$, and Yb$^{+3}$ as glass matrix modifiers, resulting in 25B$_2$O$_3$–20Bi$_2$O$_3$–45TeO$_2$–7TiO$_2$, it was found that the density of the studied glass increased from 5.67 to 6.31 gm.cm$^{-3}$, $n_b$ increased from 6.5 to 7.14 × 10$^{22}$ m$^{-3}$, and the OPD increased from 71.1 to 78.4 mol/L$^{-1}$ with an increased atomic number of incorporated rare earth ions. This is due to the increased amount of bridging oxygen (BO) and decreased number of NBOs in the prepared glass, which also led to the increased $E_{opt}$, from 1.71 to 2.8 eV, when La$_2$O$_3$ was replaced by Yb$_2$O$_3$. In addition, the molar polarizability, $\alpha_m$, decreased from 9.35 to 7.84 $\AA^3$, $\Lambda$ decreased from 1.15 to 1.03, and the refractive index decreased from 2.69 to 2.45; this was due to the good agreement with the replacement of modifiers of La$_2$O$_3$ = 1.32 $\AA^3$, Ce$_2$O$_3$ = 1.28 $\AA^3$, Sm$_2$O$_3$ = 1.16 $\AA^3$, Er$_2$O$_3$ = 0.89 $\AA^3$, Yb$_2$O$_3$ = 0.86 $\AA^3$, $\Lambda_{TeO_4}^0$ = 0.99, $\Lambda_{TeO_4^-}$ = 1.23, and $\Lambda_{TeO_3^-}$ = 0.82, in the order of La$^{+3}$ → Ce$^{+3}$ → Sm$^{+3}$ → Er$^{+3}$ → Yb$^{+3}$. The high refractive index, electronic polarizability, and optical basicity of the prepared glass containing La$_2$O$_3$ led to the achievement of significant third-order optical susceptibility. This glass may be used to produce high-quality optical nonlinear devices. The FTIR spectra confirmed the existence of TeO$_4$, TeO$_3$, BO$_4$, BO$_3$, BiO$_6$, and TiO$_4$ in the glass matrix. The glass containing Yb$^{3+}$ ions had a high value of
the TeO$_4$ phase with BO. When compared with prepared glass, Yb$^{3+}$-ion-containing glasses exhibited higher MAC values and lower HVL values, which was directly related to its high shielding characteristics. This glass is an excellent choice for use in low-energy diagnostic applications as a transparent shielding material.

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**References**

1. Xinyu, Z.; Xiaoli, W.; Hai, L.; Zhiqiang, W. Electronic polarizability and optical basicity of lanthanide oxides. *Phys. B Condens. Matter* **2017**, *392*, 132–136.

2. Fudzi, F.M.; Kamari, H.M.; Latif, A.A.; Noorazlan, A.M. Linear Optical Properties of Zinc Borotellurite Glass Doped with Lanthanum Oxide Nanoparticles for Optoelectronic and Photonic Application. *J. Nanomater.* **2017**, *2017*, 4150802. [CrossRef]

3. Selvi, S.; Marimuthu, K.; Muralidharan, G. Structural and luminescence behavior of Sm$^{3+}$ ions doped lead boro-telluro-phosphate glasses. *J. Lumin.* **2015**, *159*, 207–218. [CrossRef]

4. Hussein, K.I.; Alqahtani, M.S.; Alzahrani, K.J.; Alqahtani, F.F.; Zahran, H.Y.; Alshehri, A.M.; Yahia, I.S.; Reben, M.; Yousef, E.S. The Effect of ZnO, MgO, TiO$_2$, and Na$_2$O Modifiers on the Physical, Optical, and Radiation Shielding Properties of a TeTaNb Glass System. *Materials* **2022**, *15*, 1844. [CrossRef]

5. Selvaraju, K.; Marimuthu, K. Structural and spectroscopic studies on concentration dependent Sm$^{3+}$ doped boro-tellurite glasses. *J. Alloys Compd.* **2013**, *533*, 273–281. [CrossRef]

6. Golis, E.; Yousef, E.S.; Reben, M.; Kotynia, K.; Filipecki, J. Measurements of defect structures by positron annihilation lifetime spectroscopy of the tellurite glass TeO$_2$–P$_2$O$_5$–ZrO$_2$–LiNbO$_3$ doped with ions of rare earth elements: Er$^{3+}$, Nd$^{3+}$ and Gd$^{3+}$. *Solid State Sci.* **2015**, *50*, 81–84. [CrossRef]

7. Hussain, N.S.; Hungerford, G.; El-Mallawany, R.; Gomes, M.J.M.; Lopes, M.A.; Ali, N.; Santos, J.D.; Buddhudu, S. Absorption and Emission Analysis of RE$^{3+}$ (Sm$^{3+}$ and Dy$^{3+}$): Lithium Boro Tellurite Glasses. *J. Nanosci. Nanotechnol.* **2009**, *9*, 3672–3677. [CrossRef]

8. Elkhoshkhany, N.; Abbas, R.; El-Mallawany, R.; Hathot, S.F. Optical properties and crystallization of bismuth boro-tellurite glasses. *J. Non-Cryst. Solids* **2017**, *476*, 15–24. [CrossRef]

9. Boda, R.; Shareefuddin, M.D.; Chary, M.N.; Sayanna, R. FTIR and optical properties of europium doped lithium zinc bismuth borate glasses. *Mater. Today* **2016**, *3*, 1914–1922. [CrossRef]

10. Gupta, N.; Kaur, A.; Khanna, A.; González, F.; Pesquera, C.; Iordanova, R.; Chen, B. Structure-property correlations in TiO$_2$-Bi$_2$O$_3$-B$_2$O$_3$-TeO$_2$ glasses. *J. Non-Cryst. Solids* **2017**, *470*, 168–177. [CrossRef]

11. Sapian, I.N.; Yusof, M.I.M.; Yahia, A.K. Elastic and Structural Properties of (95-x) TeO$_2$-5La$_2$O$_3$-xTiO$_2$ Lanthanum Tellurite Glass System. *Chalcogenide Lett.* **2014**, *11*, 471–484.

12. Maheshvaran, K.; Linganna, K.; Marimuthu, K. Composition dependent structural and optical properties of Sm$^{3+}$ doped boro-tellurite glasses. *J. Lumin.* **2011**, *131*, 2746–2753. [CrossRef]
34. Arunkumar, S.; Marimuthu, K. Concentration effect of Sm$^{3+}$ ion in lead telluroborate glasses. Opt. Mater. 2011, 33, 1643–1647. [CrossRef]

35. Hager, I.Z.; El-Mallawany, R. Preparation and structural studies in the (70-x)TeO$_2$-25B$_2$O$_3$-5Li$_2$O glass system. J. Non-Cryst. Solids 2015, 103, 101–109. [CrossRef]

36. Berwal, N.; Dhankhar, S.; Sharma, P.; Kundu, R.; Punia, R.; Kishore, N. Physical, structural and optical characteristics of silicate glasses. J. Mol. Struct. 2017, 1127, 636–644. [CrossRef]

37. Komatsu, T.; Dimitrov, V.; Kaynak, S.; Assiri, A.L.; Alshehri, K.F.; Reben, M.; Yusef, E.S. Luminescence and Gamma Spectroscopy of Phosphate Glass Doped with Nd$^{3+}$ ions. J. Alloys Compd. 2017, 686, 769–784. [CrossRef]

38. Luo, M.; Sha, X.; Chen, B.; Zhang, X.; Yu, H.; Li, X.; Zhang, J.; Xu, S.; Cao, Y.; Yang, W.; et al. Optical transition properties, internal quantum efficiencies, and temperature sensing of Er$^{3+}$ doped BaGd$_2$O$_4$ phosphor with low maximum phonon energy. J. Lumin. 2019, 209, 335-3363. [CrossRef]

39. Sayyed, M.I.; Laariedh, F.; Kumr, A.; Al-Buriahi, M.S. Experimental studies on the gamma photons-shielding competence of tellurite glasses. J. Alloys Compd. 2020, 810, 135333. [CrossRef]

40. Kaur, A.; Khanna, A.; Aleksandrov, L.I. Structural, thermal, optical and photo-luminescent properties of bismuth tellurite glasses doped with rare-earth ions. J. Non-Cryst. Solids 2017, 105, 253–271. [CrossRef]
41. Pascuta, P.; Pop, L.; Rada, S.; Bosca, M.; Culea, E. The local structure of bismuth borate glasses doped with europium ions evidenced by FT-IR spectroscopy. J. Mater. Sci. Mater. Electron. 2007, 19, 424–428. [CrossRef]

42. Hung, W.-C.; Fu, S.-H.; Tseng, J.-J.; Chu, H.; Ko, T.-H. Study on photocatalytic degradation of gaseous dichloromethane using pure and iron ion-doped TiO₂ prepared by the sol–gel method. Chemosphere 2007, 66, 2142–2151. [CrossRef]

43. Abdelghany, A.M. Combined DFT, deconvolution analysis for structural investigation of copper–doped lead borate glasses. Open Spectrosc. J. 2012, 6, 9–14. [CrossRef]

44. Elkhoshkhany, N.; Khatab, M.; Kabary, M.A. Thermal, FTIR and UV spectral studies on tellurite glasses doped with cerium oxide. Ceram. Int. 2018, 44, 2789–2796. [CrossRef]

45. Elkhoshkhany, N.; El-Mallawany, R.; Syala, E. Mechanical and thermal properties of TeO₂–Bi₂O₃–V₂O₅–Na₂O–TiO₂ glass system. Ceram. Int. 2016, 42, 19218–19224. [CrossRef]

46. Kaur, A.; Khanna, A.; González, F.; Pesquera, C.; Chen, B. Structural, optical, dielectric and thermal properties of molybdenum tellurite and borotellurite glasses. J. Non-Cryst. Solids 2016, 444, 1–10. [CrossRef]

47. Eevon, C.; Halimah, M.; Zakaria, A.; Azurahanim, C.; Azlan, M.; Faznny, M. Linear and nonlinear optical properties of Gd³⁺ doped zinc borotellurite glasses for all-optical switching applications. Results Phys. 2016, 6, 761–766. [CrossRef]

48. Wang, M.; Cheng, J.; Li, M. Effect of rare earths on viscosity and thermal expansion of soda-lime-silicate glass. J. Rare Earths 2010, 28, 308–311. [CrossRef]

49. Divina, R.; Naseer, K.A.; Marimuthu, K.; Alajerami, Y.S.M.; Al-Buriahi, M.S. Effect of different modifier oxides on the synthesis, structural, optical, and gamma/beta shielding properties of bismuth lead borate glasses doped with europium. J. Mater. Sci. Mater. Electron. 2020, 31, 21486–21501. [CrossRef]

50. Chen, Q.; Naseer, K.; Marimuthu, K.; Kumar, P.S.; Miao, B.; Mahmoud, K.; Sayyed, M. Influence of modifier oxide on the structural and radiation shielding features of Sm³⁺-doped calcium telluro-fluoroborate glass systems. J. Aust. Ceram. Soc. 2020, 57, 275–286. [CrossRef]

51. Sathiyapriya, G.; Naseer, K.A.; Marimuthu, K.; Kavaz, E.; Alalawi, A.; Al-Buriahi, M.S. Structural, optical and nuclear radiation shielding properties of strontium barium borate glasses doped with dysprosium and niobium. J. Mater. Sci. Mater. Electron. 2021, 32, 8570–8592. [CrossRef]

52. Chanthima, N.; Kaewkhao, J. Investigation on radiation shielding parameters of bismuth borosilicate glass from 1 keV to 100 GeV. Ann. Nucl. Energy 2013, 55, 23–28. [CrossRef]

53. Chanthima, N.; Kaewkhao, J.; Limkitjaroenporn, P.; Tuscharoen, S.; Kothan, S.; Tungjai, M.; Kaewjaeng, S.; Sarachai, S.; Limsuwan, P. Development of BaO–ZnO–B₂O₃ glasses as a radiation shielding material. Radiat. Phys. Chem. 2017, 137, 72–77. [CrossRef]

54. Cheewasukhanont, W.; Limkitjaroenporn, P.; Sayyed, M.I.; Kothan, S.; Kim, H.J.; Kaewkhao, J. High density of tungsten gadolinium borate glasses for radiation shielding material: Effect of WO₃ concentration. Radiat. Phys. Chem. 2022, 192, 109926. [CrossRef]