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Structural, optical, mechanical, and gamma-ray shielding properties of Er_2O_3-doped germano-tellurite-borate glasses

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This study reports the fabrication of a new germano-tellurite-borate glass series for optical and gamma-ray shielding applications. The chemical formula $20TeO_2 + 10GeO_2 + (35 - y)B_2O_3 + 35MgO + yEr_2O_3$ describes the fabricated germano-tellurite-borate glass series, where y takes values of 1.25, 2.5, 3.75, and 5 mol%. An X-ray diffractometer (XRD) was used to confirm the amorphous phase of the fabricated glasses. Furthermore, the impact of partial replacement of Er_2O_3 for B_2O_3 on the optical properties of the examined glasses was evaluated based on the UV-Vis absorption spectra, which were detected using a spectrophotometer at wavenumbers ranging from 200 to 1200 nm. The refractive index of the examined glasses increased from 2.620 to 2.270 when the Er_2O_3 increased from 1.25 to 5 mol%, respectively. Also, the impact of partial replacement of Er_2O_3 for B_2O_3 on the mechanical properties of the investigated glasses was evaluated based on Makishima and Mackenzie's theory. An increase in the Er_2O_3 content from 1.25 to 5 mol% enhances the hardness of the investigated glasses from 5.217 to 5.263 GPa, respectively. Additionally, the γ-ray protecting parameters were estimated using Monte Carlo simulation over a broad 0.0332–2.506 MeV energy interval. According to the acquired findings, the prepared samples' linear attenuation coefficient enhances by 54.94%, 11.09%, and 6.94%, respectively, at the 0.059, 0.511, and 2.506 MeV γ-ray energies as the Er_2O_3 increases over a concentration of 1.25–5 mol%.

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1. Introduction

Researchers have recently become more interested in exploring improved glass systems for novel industrial and technological uses.[1–5] Due to attractive properties, such as excellent optical transparency, high refractive index, low melting point, chemical durability, thermal stability, favorable electrical properties, and adequate radiation shielding properties, borotellurite glasses have gained considerable attention.[6–9] These fascinating properties make borotellurite glasses promising materials for different applications, including radiation shielding materials, optical fibers and waveguides, non-linear optical devices, photonic devices, luminescent materials, biomedical applications, memory devices, and data storage.[10–15]

TeO_2 cannot form a glass under typical quenching situations unless an additional constituent is added. Tellurite glasses, hence, require the inclusion of secondary components like heavy metal oxides, and rare earth oxides. TeO_2 combined with additional components produces glasses that are durable and allow for the control of desired characteristics.[3,16,17]

To improve the borotellurite glass network's density and effective atomic number, GeO_2 and Er_2O_3 are added. These advantageous characteristics led to the selection of GeO_2 and Er_2O_3 as additional components in our attempt to produce borotellurite glasses.[18] Traditionally, the widespread use of lead-based glasses has achieved gamma-ray radiation shielding from other ionizing, human-hazardous radiation. Due to their toxicity, lead-based glasses are not preferable in radiation shielding applications, and thus researchers are trying to develop lead-free glasses for radiation shielding purposes.

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The literature[19–24] highlights several efforts to replace lead-based glasses with lead-free alternatives or radiation-shielding glasses. The borotellurite glasses with HMO exhibit remarkable shielding ability equal to or exceeding that of different glass systems. Consequently, comprehending borotellurite-based glasses' shielding efficiency and their ability to attenuate ionizing radiation is essential for their application in radiation environments.[25,26]

The Monte Carlo N-particle transport code fifth version (MCNP5) is a simulation program developed by the Los Alamos National Laboratory, utilizing the mathematical technique of Monte Carlo simulation to solve the transport equation for studying radiation–material interactions. It can operate using many forms of radiation exposure, and in terms of radiation sources, it can utilize neutrons, photons, and electrons. MCNP serves as a functional instrument for evaluating radiation interaction characteristics in various mixes and compounds, facilitating shielding and energy absorption in human organs and tissues through the application of physics models for nuclear cross-sections and particle interaction libraries.[27,28]

On the other hand, XCOM represents a useful software resource for the study of radiation shielding that can estimate glasses' (and other composites) mass attenuation coefficient (MAC) at different energy levels.[29] This software and other similar software (such as Phy-X software) support the simulation and experimental works by allowing researchers to define their materials using the composition and the density of the materials at certain energies.[30]

The novelty of the current work is to fabricate a new germano-tellurite-borate glass series described by the chemical formula $20TeO_2 + 10GeO_2 + (35 - y)B_2O_3 + 35MgO + yEr_2O_3$; y = 1.25, 2.5, 3.75, and 5 mol%. The influence of partial substitution of Er_2O_3 for B_2O_3 on the structural, optical, mechanical, and gamma-ray shielding capacity was examined using various experimental and theoretical methods.

2. Methodology

2.1. Sample fabrication

In the present case, a series of erbium oxide doped-germanate tellurite borate glasses were fabricated based on the chemical formula $20TeO_2 + 10GeO_2 + (35 - y)B_2O_3 + 35MgO + yEr_2O_3$ with y values of 1.25, 2.5, 3.75, and 5 mol%. The high-purity chemicals were from established suppliers such as Sigma-Aldrich. The desired chemicals were weighed to prepare a 15 g patch using the molar proportion shown in Table 1. A plastic container that is labeled for each composition was prepared, and all chemicals involved in the desired glass samples were blended and mixed for 20 min so the homogeneous structure could be ensured. Er1, Er2, Er3, and Er4 powders were then poured into a crucible made of high alumina and placed for 20 min in a 1100 °C electric muffle furnace for melting. The Er1, Er2, Er3, and Er4 molten glass was poured on a pre-heated stainless-steel disc, with the samples then cooling to room temperature gradually to negate a sudden high change of the temperature that leads to cracking. To release any internal stress in the glass samples, 5 h of annealing was conducted in another furnace at 350 °C. The final Er1, Er2, Er3, and Er4 glass samples are presented in Fig. 1, with further structural and optical characterizations carried out. The origin software was used to plot all figures in this manuscript.

Table 1 Chemical formula of the erbium-oped G-T-B glass system

	Chemical composition (mol%)					
Glass code	B_2O_3	TeO_2	GeO_2	MgO	Er_2O_3	Density (g cm^{-3})
Er1	33.75	20.00	10.00	35.00	1.25	3.750 ± 0.059
Er2	32.50	20.00	10.00	35.00	2.50	3.828 ± 0.056
Er3	31.25	20.00	10.00	35.00	3.75	3.905 ± 0.066
Er4	30.00	20.00	10.00	35.00	5.00	3.982 ± 0.072

The density (ρ, g cm^{-3}) of the fabricated Er glasses was measured according to Archimedes' principle in eqn (1).[31,32]

$$\rho_{glass}\left(\text{g cm}^{-3}\right) = \frac{M_a}{(M_a - M_i)} \times \rho_{water} \quad (1)$$

In eqn (1), M_a and M_i refer to the mass of fabricated Er glasses in air and immersed in water, while ρ_{glass} refers to the density of water ($\approx$1 g cm^{-3}). The uncertainty in the measured densities for the examined samples in ±1.8%.

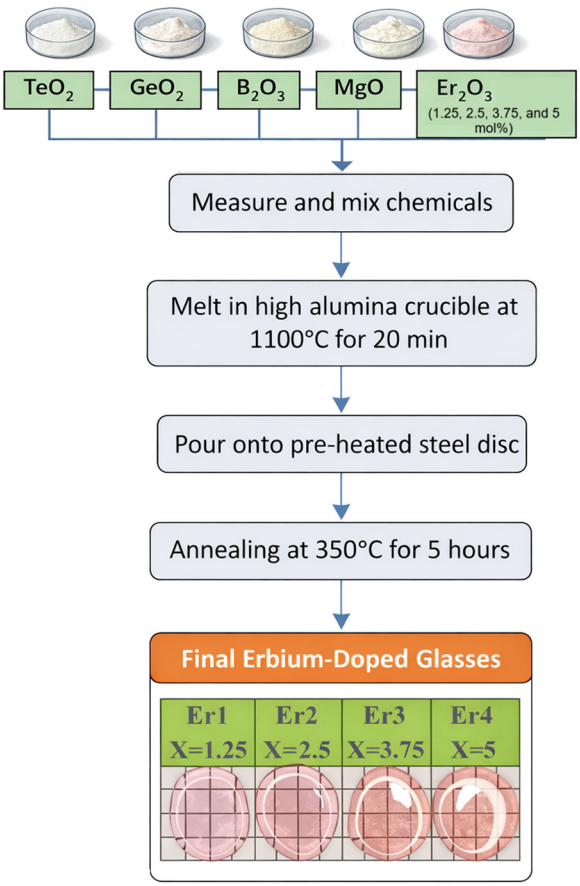

Fig. 1 A photograph of the erbium-doped G-T-B glass system.

2.2. Glass characterization and optical properties

In the current work, a Shimadzu XRD-6000 was used to measure the sample's X-ray diffraction (XRD) profiles in the 10–80° range to investigate the synthesized glasses' nature. The UV absorption spectra (3101, Japan; wavelength range: 200–1200 nm) were used to examine the optical characteristics. The absorbtion edge was used to determine the band gap (E_g) value according to Mott and Davis equation,[33]

$$h\nu\alpha = A(h\nu - E_g)^n \quad (2)$$

where $h\nu$, A, and α respectively represent the photon energy, constant, and absorption coefficient. Meanwhile, determination of the Urbach energy (E_U) used eqn (3):

$$\ln(\alpha) = \ln(\alpha_0) + \frac{h\nu}{E_U} \quad (3)$$

In this case, a_0 represents the corresponding constant. Based on E_g values, eqn (4) facilitated the determination of the refractive index (n):

$$\frac{(n^2-1)}{(n^2+2)} = 1 - \sqrt{\frac{E_g}{20}} \quad (4)$$

Several equations from our earlier study[34] were used to compute the following parameters: optical basicity (Λ), metallization, electron polarizability (α_0), and optical electronegativity (χ).

2.3. Mechanical properties

The Archimedes principle, as employed in ref. 35 was used to quantify the density of fabricated samples. For the mechanical properties' evaluation, the study used the Makishima and Mackenzie (M–M) model.[36] The main model components, the packing density (V_t) and the dissociation energy (G_t), are presented in eqn (5) and (6):[37]

$$V_t = \sum_i \frac{V_i x_i}{V_m} \quad (5)$$

$$G_t = \sum_i x_i G_i \quad (6)$$

where V_m, G_i, x_i, and V_i represent the molar volume, dissociation energy, mole ratio, and oxide packing factor, respectively. Equations previously given were used to compute the remaining mechanical characteristics.[38,39]

2.4. Calculation of the γ-ray shielding characteristics

The γ-ray shielding parameters' evaluation was performed based on the MCNP,[40] through which the shielding parameters were evaluated by estimating the prepared Er glass samples' γ-photons in terms of the track length (TL). The simulation processes were performed so that virtually all known γ-ray energies in the 0.0332–2.506 MeV interval would be covered. For accurate simulated data, an input file with well-arranged geometry should be created. Fig. 2 presents the created geometry, which comprises numerous cards (*e.g.*, cell, cutoff, importance, material, source definition, surface, and tally), under which the details of the geometry should be introduced. According to the generated input file, the cell is deemed the smallest building unit inside the geometry, which comprises many cells. Each cell has a definite cell number and density. The cell is also surrounded by many surfaces that are defined and described under the surface card section, such as the shape and dimensions surrounding each cell in the input file. For example, the external shielding cell comprising pure lead (density: 11.34 g cm^{-3}) is cylindrical, filled with dry air, and has the following measurements: thickness: 5 cm, diameter: 25 cm, height: 35 cm. The individual's elemental chemical composition was added to the material card. Moreover, the tally used to estimate the TL is F4, with the cutoff card set up to cease interactions following 10^6 historical emissions. Further simplification was achieved by setting the PHY card to (PHYS: P 1 0 0 0), thus indicating the absence of coherent scattering, Bremsstrahlung, photoelectric interaction fluorescence, or binding effects in photon scattering greater than 1 MeV. Finally, the output file's relative error produced by the simulation process was in the ±0.1 range. Next, the simulated TL according to eqn (7) was used for the simulated LAC evaluation.

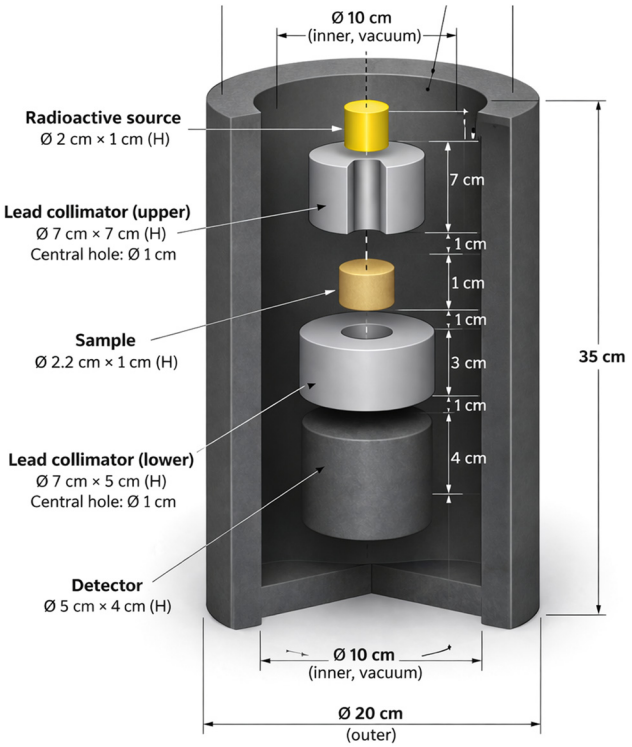

Fig. 2 A 3D representation for the geometry according to MCNP-5's input file.

Then, the obtained TL from the output file was employed for the determination of the prepared Er glasses' linear attenuation coefficient (LAC, cm^{-1}). Eqn (8)–(12) facilitated evaluation of the γ-ray shielding parameters, including the MAC (cm^2 g^{-1}), half-value layer (HVL, cm), thickness equivalent lead (D_{eq}, cm), and radiation protection efficiency (RPE, %) according to the LAC, I_o, and I_t values.[41–43]

$$\mathrm{LAC}\ (\mathrm{cm}^{-1}) = \frac{1}{x}\ln\left(\frac{I_o}{I_t}\right) \quad (7)$$

$$\text{MAC}\ (\text{cm}^2\ \text{g}^{-1}) = \frac{\text{LAC}\ (\text{cm}^{-1})}{\rho\ (\text{g cm}^{-3})} \quad (8)$$

For the non-shielded radioactive source, I_o is the detected activity. Using a thickness x (cm) from the prepared Er glass, the I_o values reduced to be I_t.

The half value thickness (HVL, cm) is the thickness of the fabricated Er glasses that can reduce the I_o photons by 50% (*i.e.*, I_t = 50%I_o). The HVLs are related to the LACs of the examined Er glass samples, as exhibited in eqn (9).

$$\text{HVL}\ (\text{cm}) = \frac{\ln(2)}{\text{LAC}} \quad (9)$$

Next, the obtained LAC, I_o, and I_t values were employed for the radiation shielding parameters' evaluation, including the RPE (%), thickness equivalent lead (Δ_{eq}, cm), and transmission factor (TF, %), according to eqn (10)–(12).

The thickness equivalent lead (Δ_{eq}, cm) represents the thickness of the Er glass sample that has shielding capacity equal to that of a 1 cm thickness of pure lead. The Δ_{eq} values depend mainly on the LAC of pure lead and the fabricated glasses, as presented in eqn (10).

$$\Delta_{eq}\ (\text{cm}) = \frac{\text{LAC}_{\text{lead}} \times x_{\text{lead}}}{\text{LAC}_{\text{Er glasses}}} \quad (10)$$

The transmission factor (TF, %) represents the percentage of transmitted photons (I_t) relative to the initial number of photons (I_o). It can be calculated according to eqn (11).[44,45]

$$\text{TF}\ (\%) = \frac{I_t}{I_o} = \times 100 \quad (11)$$

The radiation protection efficiency (RPE, %) describes the percentage of photons absorbed (I_a) within the Er glass layer relative to the initial photon (I_o) number. The RPEs can be calculated according to eqn (12), where the I_a photons are I_o–I_t photons.

$$\text{RPE}\ (\%) = \frac{I_a}{I_o} = \frac{(I_o - I_t)}{I_o} \times 100 \quad (12)$$

3. Results and discussion

3.1. X-ray diffraction

The XRD results for all glass samples are presented in Fig. 3, where at 28 and 50 degrees two broad bands can be seen. In terms of the glass system, a lack of long order is indicated by the peaks, meaning that the current sample's network is amorphous.

3.2. Optical properties

Evaluating and comprehending a glass system's optical properties is vital for using the glass in different applications. Measuring the absorption spectra for any glass system is considered the first step in evaluating optical properties. Fig. 4 shows the absorption spectra for the different Er_2O_3 concentration-doped glass samples. Nine absorption bands related to the ground state ($^4I_{15/2}$) and different excited state ($4G_{11/2}$, $4G(1)_{9/2}$, $4F_{3/2}$–$4F_{5/2}$, $4F_{7/2}$, $2H_{11/2}$, $4S_{3/2}$, $4F_{9/2}$, $4I_{9/2}$, and $4I_{11/2}$) transitions can be seen, which correspond to 378, 407, 450, 488, 523, 543, 652, 794, and 977 nm. At 523 nm, there is also evidence of a hypersensitive transition ($^4I_{15/2} \rightarrow {}^2H_{11/2}$) following the selection rule $|\Delta S| = 0$, $|\Delta L| \leq 2$, $|\Delta J| \leq 2$. The absorption peaks' intensity showed gradual enhancement with the addition of Er_2O_3, which is in agreement with Mhareb *et al.*'s findings.[46,47]

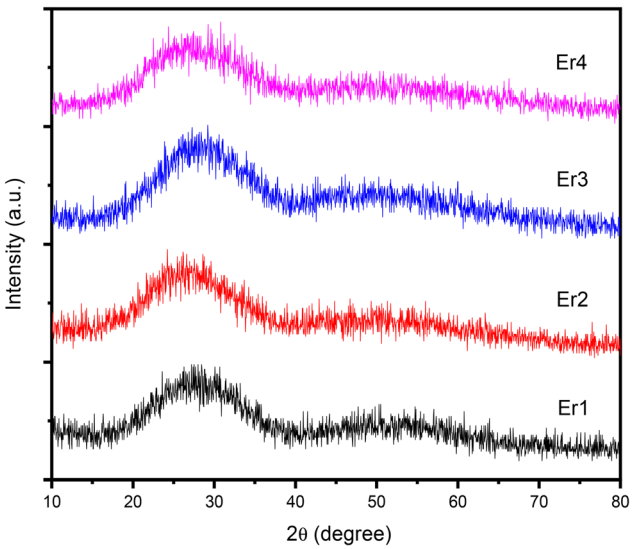

Fig. 3 XRD results for all glass samples.

Mott and Davis suggested a relation to evaluate the energy band gap using the absorption data. Fig. 5 and 6 show the Tauc plot, representing the relation between $h\nu$ and $(\alpha h\nu)^2$. The synthesized glass system's optical properties are listed in Table 2. The Er1, Er2, Er3, and Er4 band gap (E_g) values are 3.553, 3.532, 3.521, and 3.516 eV, respectively. The gradual reduction can be noted by adding Er_2O_3 instead of B_2O_3, which relates to the formation of a novel valence–conduction band localization due to defects. Conversely, Table 2 assesses and lists the glass system's Urbach energy (E_U), where the E_U values

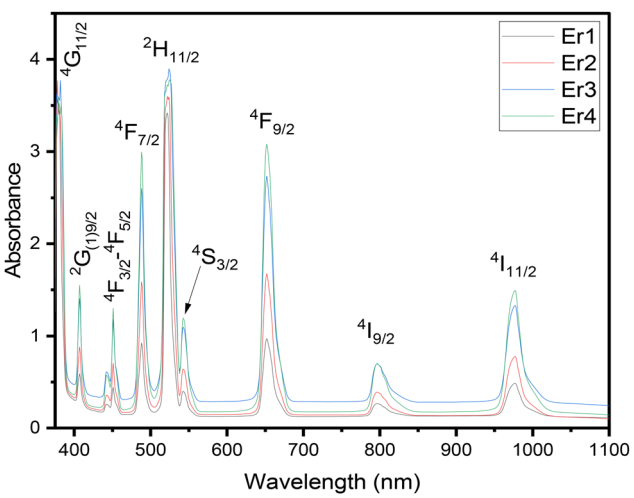

Fig. 4 UV-vis absorption spectra for the Er_2O_3-doped glass samples.

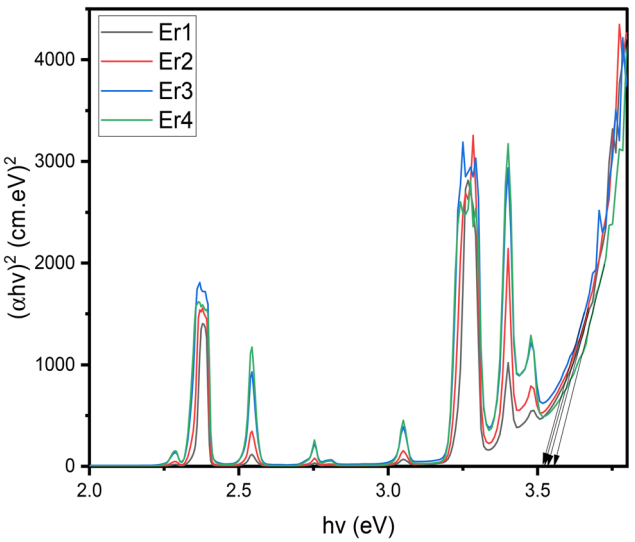

Fig. 5 Indirect band gap for the Er_2O_3-doped glass samples.

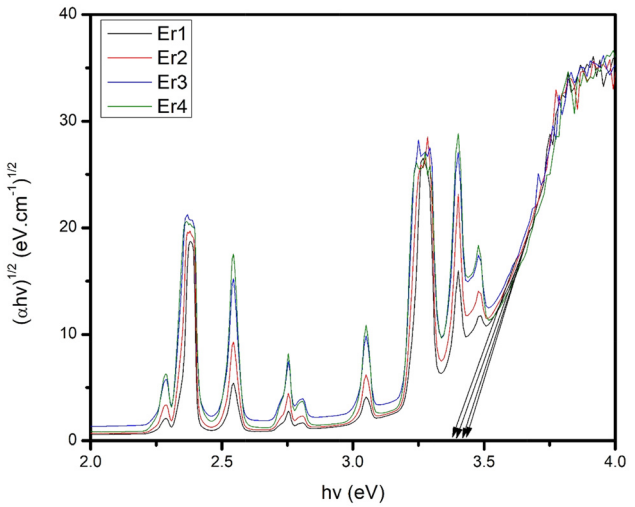

Fig. 6 Direct band gap for the Er_2O_3-doped glass samples.

can be seen to increase gradually by replacing B_2O_3 with Er_2O_3, and their values are 0.266, 0.268, 0.277, and 0.278 eV for Er1, Er2, Er3, and Er4. Such an increment is aligned with the band gap value reduction, indicating defects in glass samples. The glass samples' E_g–E_U relation is illustrated in Fig. 7.

The glass samples' refractive index rises with increased Er_2O_3 content, referring to the increase of nonbridging oxygen (NBO) and polarizability. This argument is affirmed by electron polarizability with a 2.640 to 2.649 increase for Er1 and Er4. There was a 0.578 to 0.580 reflection loss value rise for Er1 and Er4, while the transmission reduced from 0.739 to 0.737 for Er1 and Er4. This trend can be related to the glass systems' increased refractive index. The metallization values lie between 0.421 and 0.419 for Er1 and Er4, which refers to the current glasses' semiconductor behaviors. Lastly, there was an inverse optical electronegativity–optical basicity relation. Namely, a 0.955 to 0.945 optical electronegativity reduction for Er1 and Er4, where this reduction lessened the glass system's link strength. Meanwhile, there was a 1.222 to 1.227 optical basicity increase for Er1 and Er4, representing ionic rather than covalent bond formation. This assumption indicates the glass's reduced stability, in line with forming NBO.

3.3. Mechanical and structural properties

The mechanical and structural properties can be used to evaluate glass stability. Theoretical models such as M–M are widely utilized for the calculation of the glasses' mechanical properties.[36] As the methodology part illustrated, the M–M model is reliant on dissociation energy (G_t) and packing density (V_t). Initially, we should analyze the rise in molar volume and density values described in Tables 1 and 3. This rise refers to reducing the glass compactness with increasing Er_2O_3 content. This result aligns with packing density values, which were reduced by adding Er_2O_3, as shown in Fig. 8. Besides, the dissociation energy for the glass samples was reduced from 17.270 to 17.236 kcal cm^{-3} for the Er1 and Er4 samples due to a weak bond (Er_2O_3) replacing a strong one (B_2O_3). For example, the dissociation energy for B_2O_3 and Er_2O_3 is 18.619 and 17.696 kcal cm^{-3}, respectively. Conversely, there was a 11.301 to 12.117 cm^3 mol^{-1} oxygen molar volume increase with rising Er_2O_3 content, owing to a large ionic radius atom (Er^{3+}) being added as opposed to a small one (B^{3+}), so the large ions disturb the glass networks by taking up greater space, resulting in an open glass structure, with this argument aligned with reducing glass compactness. This result is responsible for reducing the oxygen packing density from 88.485 to 82.527 mol cm^{-3} for Er1 and Er4.

Table 2 The Er_2O_3-doped glass samples' optical parameters

	Glass codes			
Optical parameters	Er1	Er2	Er3	Er4
Indirect band gap (eV)	3.553 ± 0.02	3.532 ± 0.02	3.521 ± 0.02	3.516 ± 0.02
Direct band gap (eV)	3.437 ± 0.02	3.417 ± 0.02	3.394 ± 0.02	3.371 ± 0.02
Refractive index	2.262	2.266	2.269	2.270
Transmission	0.739	0.738	0.738	0.737
Urbach energy (eV)	0.266	0.268	0.277	0.278
Reflection loss (R)	0.578	0.579	0.580	0.580
Metallization	0.421	0.420	0.419	0.419
Optical electronegativity (χ)	0.955	0.949	0.946	0.945
Electron polarizability (α_0)	2.640	2.645	2.648	2.649
Optical basicity (Λ)	1.222	1.225	1.226	1.227

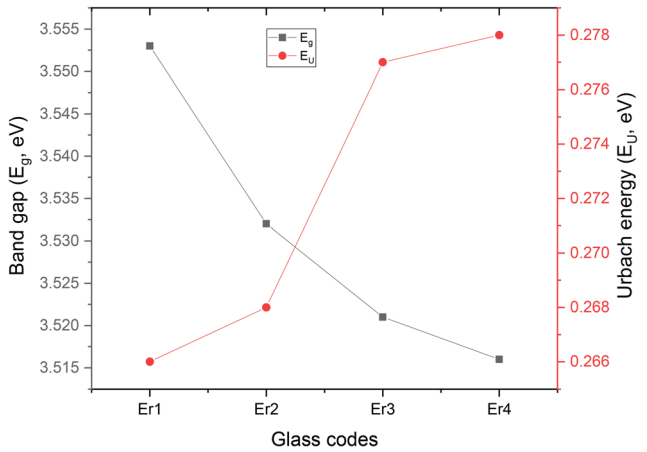

Fig. 7 The relation band gap and Urbach energy for the Er_2O_3-doped glass samples.

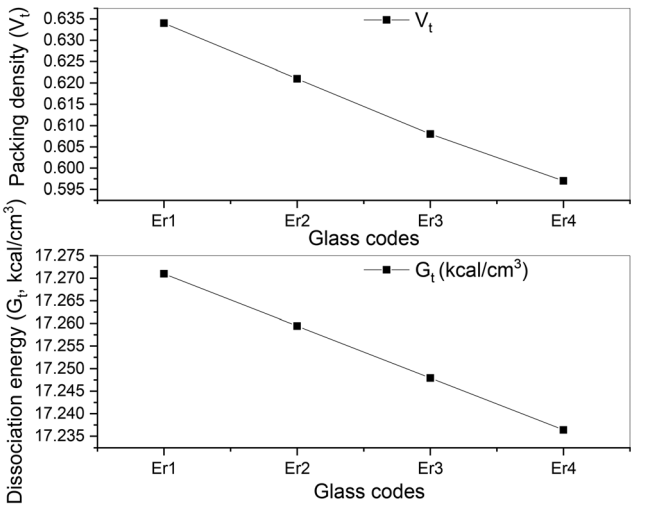

Fig. 8 Er_2O_3-doped glass samples' dissociation energy and packing density.

There was a 0.281–0.267 Poisson ratio range for Er1 and Er4 samples. This result indicates that the glass samples have good density cross-linking. At the same time, the fractal bond conductivity (d) values are in the 2.192–2.356 range, indicating that the glass network ranged from 2 to 3 dimensions. On the other hand, the hardness of the glass system was enhanced with rising Er_2O_3, referring to the glass samples' improved surface resistance against scratch tools. All elastic moduli showed a reduction by adding Er_2O_3, as Fig. 9 shows. For instance, the Shear modulus had a 38.126 to 36.228 GPa reduction for Er1 and Er4. The Young's modulus echoes this behavior and was reduced from 91.629 to 86.074 GPa for the Er1 and Er4 samples. Such elastic moduli reduction is due to a weak bond (Er–O) replacing a strong one (B–O), as mentioned above. For an evaluation of the current sample's elastic modulus, we should compare it with other glass groups, for instance, the comparative samples' Young's modulus values are (La2.5 = 90.235 GPa), (La5 = 87.15 GPa), (La7.5 = 84.484 GPa), (La10 = 82.153 GPa), (M1 = 91.657 GPa), (M2 = 90.043 GPa), (M3 = 88.538 GPa), (M4 = 87.130 GPa), (Nd2.5 = 89.993 GPa), (Nd5.0 = 86.697 GPa), (Nd7.5 = 83.858 GPa), (Pb1 = 90.620 GPa), (Pb2 = 87.296 GPa), (Pb3 = 84.030 GPa), and (Pb4 = 80.818 GPa), Y2.5 = 90.747 GPa), (Y5 = 87.887 GPa), and

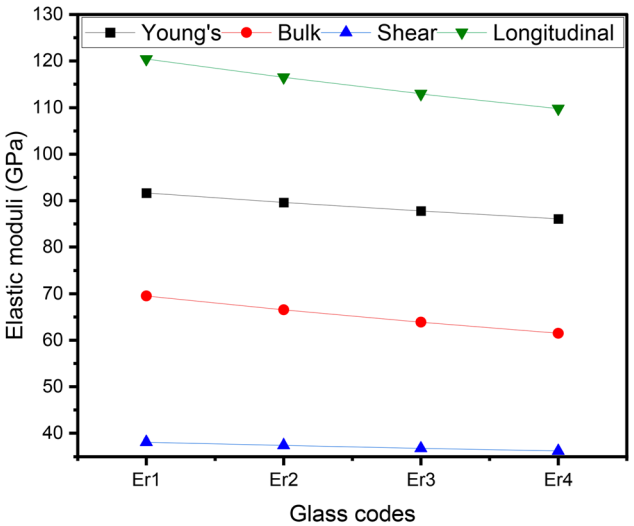

Fig. 9 Elastic moduli for the Er_2O_3-doped glass samples.

Table 3 Mechanical parameters for glass samples doped with Er_2O_3

	Glass codes			
Mechanical parameters	Er1	Er2	Er3	Er4
Molar volume (V_m, cm^3 mol^{-1})	22.602	23.168	23.711	24.234
Oxygen Molar Volume (OMV, cm^3 mol^{-1})	11.301	11.584	11.855	12.117
Oxygen Packing Density (OPD, mol cm^{-3})	88.485	86.324	84.345	82.527
Packing factor (V_i)	14.344	14.388	14.432	14.476
Packing density (V_t)	0.634	0.621	0.608	0.597
Poisson ratio (σ)	0.281	0.276	0.271	0.267
Hardness (H, GPa)	5.217	5.233	5.248	5.263
Dissociation energy (G_t, kcal cm^{-3})	17.270	17.259	17.247	17.236
Young's modulus (Y, GPa)	91.629 ± 1.441	89.605 ± 1.310	87.761 ± 1.483	86.074 ± 1.556
Bulk modulus (GPa)	69.556	66.563	63.893	61.501
Shear modulus (GPa)	38.126	37.434	36.804	36.228
Longitudinal modulus (GPa)	120.392	116.475	112.966	109.806
Fractal bond conductivity (d)	2.192	2.249	2.304	2.356

(Y7.5 = 85.244 GPa).[36,48–52] The Er1 sample showed better results than the other samples, apart from M1.

3.4. Radiation shielding properties

As shown in Fig. 10(a) and (b), over the investigated γ-ray energy interval of 0.0332–2.506 MeV the LACs decreased exponentially under the influence of the interactions of photoelectric (PE) and Compton scattering (CS). The greatest LACs were found at 0.0332 MeV within the chosen energy interval. For Er1, Er2, Er3, and Er4 glass samples, the LACs respectively reach 44.725 cm^{-1}, 45.539 cm^{-1}, 46.731 cm^{-1}, and 48.144 cm^{-1}. With a gradual increase in γ-ray energy in the 0.0332–0.122 MeV range, the LACs decreased by 95.39%, 94.78%, 94.22%, and 93.70% for the glass samples Er1, Er2, Er3, and Er4, in that order, under the PE interaction influence, as illustrated in Fig. 10(a). This large reduction in LACs is explained by the decreasing interaction cross-section with γ-ray energy increase, whereby the cross-section fluctuates with $E_\gamma^{-3.5}$. Subsequently, with the advancement of CS interaction over the interval of 0.244–2.506 MeV, the prepared glass samples' LACs moderately fall. As shown in Fig. 10(b), the LACs decreased through 0.244–2.506 MeV throughout the following values: 0.624–0.144 cm^{-1} (Er1), 0.682–0.147 cm^{-1} (Er2), 0.740–0.150 cm^{-1} (Er3), and 0.798–0.154 cm^{-1} (Er1). The observed mild LAC decline in the prepared samples across the CS interval can be explained by the interaction cross-section's proportionality to E_γ^{-1}.

A comparison of the simulated LACs from MCNP and the XCOM database-calculated values is shown in Table 4, where the differences are up to ±1%, respectively. As illustrated in Fig. 11, comparison was drawn between the prepared Er samples' LACs *versus* those of many commercial radiation shielding glasses as well as some comparable samples from the literature in order to validate the prepared glass samples'

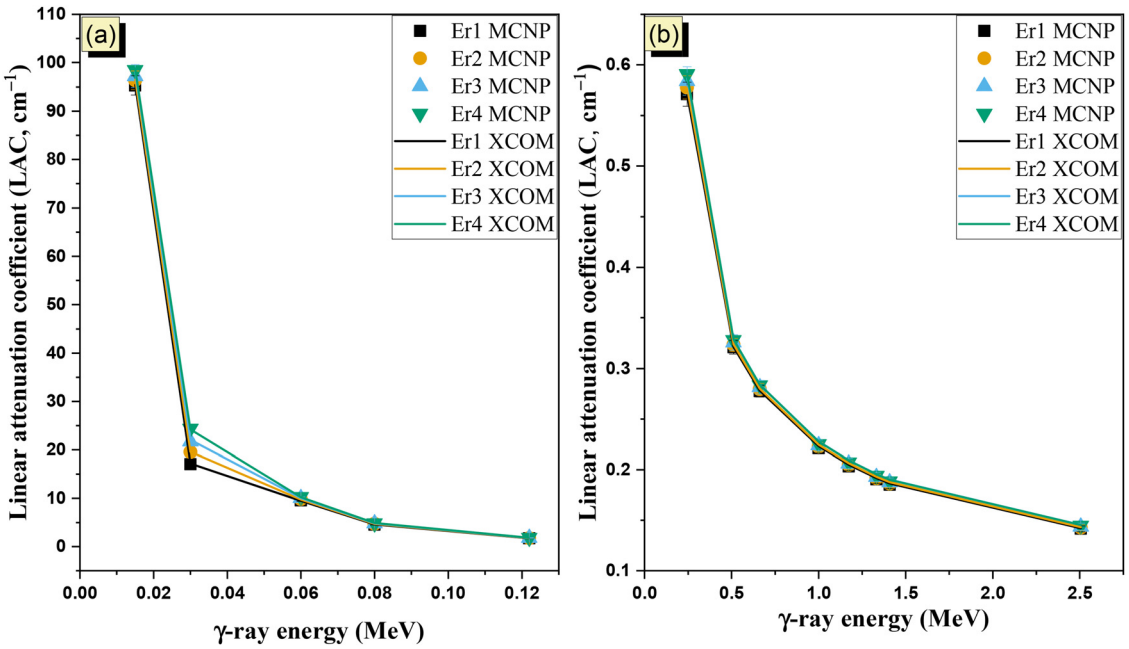

Fig. 10 The linear attenuation coefficient (LAC) variation *versus* the γ-ray energies at the (a) photoelectric interval and (b) Compton scattering interval.

Table 4 Comparing the linear attenuation coefficient obtained from the simulation code MCNP-5 and those calculated using the XCOM database

Energy (MeV)	Linear attenuation coefficient (cm^{-1})											
	E1			E2			E3			E4		
	MCNP ± 0.1	XCOM ± 1	Diff (%)	MCNP ± 0.1	XCOM ±1	Diff (%)	MCNP ± 0.1	XCOM ± 1	Diff (%)	MCNP ± 0.1	XCOM ± 1	Diff (%)
0.0332	44.725	44.325	-0.9	45.539	45.706	0.4	46.731	47.055	0.7	48.144	48.381	0.5
0.059	12.038	12.041	0.0	14.297	14.313	0.1	16.369	16.483	0.7	18.651	18.576	−0.4
0.081	5.397	5.366	−0.6	6.410	6.366	−0.7	7.351	7.326	−0.3	8.268	8.247	−0.3
0.122	2.060	2.042	−0.9	2.378	2.383	0.2	2.702	2.709	0.2	3.034	3.024	−0.3
0.244	0.624	0.625	0.1	0.682	0.683	0.2	0.740	0.739	−0.1	0.798	0.793	−0.6
0.356	0.428	0.429	0.2	0.453	0.454	0.3	0.477	0.478	0.3	0.500	0.501	0.3
0.511	0.331	0.332	0.2	0.344	0.345	0.2	0.356	0.357	0.2	0.368	0.369	0.2
0.662	0.284	0.285	0.2	0.293	0.293	0.2	0.301	0.302	0.2	0.309	0.310	0.2
1.173	0.206	0.208	1.0	0.210	0.213	1.1	0.215	0.217	1.1	0.219	0.221	1.2
1.332	0.193	0.195	0.8	0.197	0.199	0.9	0.201	0.203	1.0	0.205	0.207	1.0
1.408	0.188	0.189	0.8	0.191	0.193	0.9	0.195	0.197	0.9	0.199	0.201	1.0
2.506	0.144	0.144	0.4	0.147	0.148	0.4	0.150	0.151	0.5	0.154	0.154	0.5

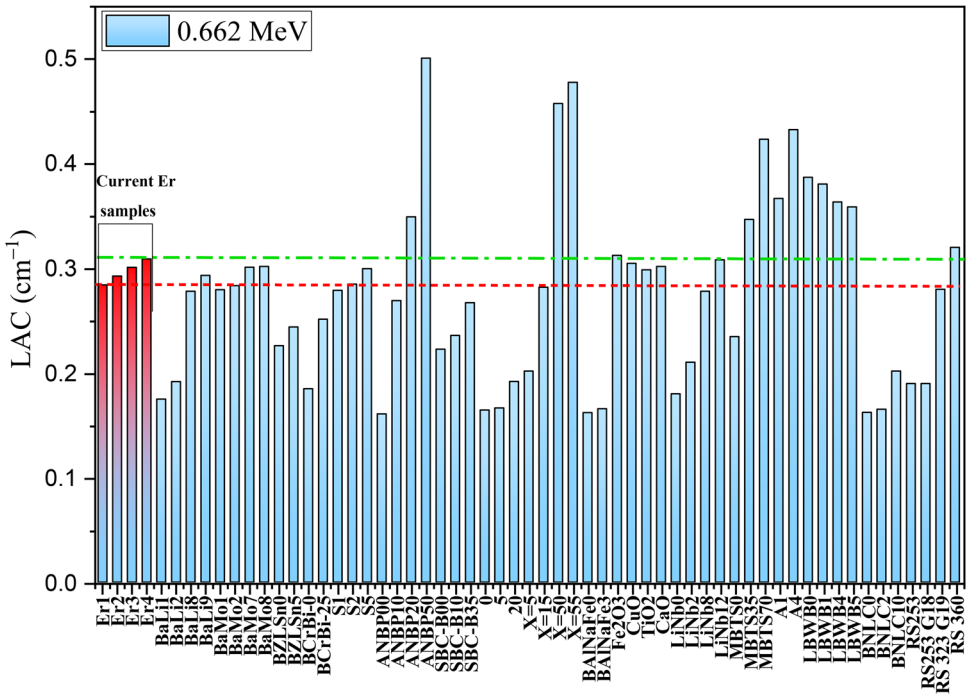

Fig. 11 Comparison of the prepared Er glass samples' LAC *versus* those of commercial and similar glass samples from the literature.

shielding capacity. As clarified in Fig. 11, at 0.662 MeV the Er1, Er2, Er3, and Er4 prepared glass samples' LACs are respectively 0.284, 0.293, 0.301, and 0.309 cm^{-1}, and they are thus comparable to those of glass samples selected from the literature[53–57] BaLi8, BaLi9, BaMo1, BaMo2, BaMo7, BaMo8, S1, S2, S5, X = 15, Fe_2O_3, CuO, TiO_2, CaO, LiNb8, and LiNb12 at 0.662 MeV have respective LACs of 0.278, 0.293, 0.280, 0.283, 0.301, 0.302, 0.279, 0.285, 0.300, 0.282, 0.312, 0.305, 0.299, 0.302, 0.278, 0.308, and 0.280 cm^{-1}. Moreover, the LACs of the fabricated Er1 glass samples were close to those for the commercial RS 323 G19 (0.280 cm^{-1}) radiation shielding glass which in its chemical composition has PbO of approximately 33 wt%. The fabricated sample Er4 also has LAC at 0.662, close to that of the RS 360 commercial radiation shielding glass (0.320 cm^{-1}) which contains a high concentration of PbO that reaches 45 wt%.[58] Moreover, the fabricated Er glass samples' LACs are high in comparison to those reported for similar glasses selected from the literature,[53,56,57,59–66] for example: BaLi1, BaLi2, BZLSn0, BZLSn5, BCrBi-0, BCrBi-25, ANBP00, ANBP10, SBC-B00, SBC-B10, SBC-B35, 0, 5, 20, X = 5, BAlNaFe0, BAlNaFe3, LiNb0, LiNb2, MBTS0, BNLC0, BNLC2, BNLC10 with respective LACs of 0.175, 0.192, 0.226, 0.244, 0.185, 0.251, 0.161, 0.269, 0.222, 0.236, 0.267, 0.165, 0.167, 0.192, 0.202, 0.162, 0.166, 0.180, 0.210, 0.235, 0.162, 0.165, and 0.202 cm^{-1}. Also, the LACs of the current study's fabricated Er1–Er4 glasses are greater than those for the commercial RS253 (0.19 cm^{-1}) and RS253 G18 (0.19 cm^{-1}) radiation shielding glasses at 0.662 MeV.[58] In contrast, the LACs of Er1–Er4 are below those found in the literature[56,61,65,67,68] for glass samples ANBP20, ANBP50, X = 50, X = 55, MBTS35, MBTS70, A1, A4, LBWB0, LBWB1, LBWB4, and LBWB5 with LACs of 0.349, 0.501, 0.458, 0.478, 0.347, 0.423, 0.367, 0.433, 0.387, 0.380, 0.363, and 0.359 cm^{-1}, respectively.

Based on the fabricated Er glasses' measured ρ values and simulated LACs, the MACs were evaluated for Er1–Er4 glasses across the 0.0332–2.506 MeV interval, as Fig. 12(a) shows. The increase of γ-ray energy has an influence on the MACs similar to that illustrated in Fig. 10 for the LACs, where the γ-ray energy rise exponentially reduces the MAC through the PE and CS interaction effect. As seen in Fig. 12(a), the 0.0332–2.506 MeV increase declines the MACs throughout 11.927–0.038, 11.896–0.038, 11.967–0.039, and 12.090–0.039 cm^2 g^{-1} for the Er1, Er2, Er3, and Er4 glass samples, respectively.

Fig. 12(b) illustrates the fabricated Er glass samples' inverse LAC–HVL relationship, as stated in eqn (9). This relationship causes increased HVLs with greater γ-ray energy. With a 0.0332 to 2.506 MeV γ-ray energy increase, the HVLs for the developed Er1, Er2, Er3, and Er4 glass samples increased throughout 0.015–4.822, 0.015–4.712, 0.015–4.608, and 0.014–4.509 cm, respectively. The primary cause of the increase in HVLs is the fabricated Er glass samples' decreased LACs; a decrease in the γ-photons' cross-section interaction is observed when the γ-ray energy is increased. As a result, while (I_t) photons increased, the interaction probability and (I_a) photons decreased. Therefore, the HVLs rise to approve the I_t = 50% I_o relation.

Furthermore, as shown in eqn (11), a (I_t) photon increase also increases the (I_t/I_o) ratios and TFs for the prepared Er glass samples. With a 0.122 and 2.506 MeV γ-ray energy increase, Fig. 12(d) reveals a TF increase over the 12.75–86.61% (Er1), 9.27–86.32% (Er2), 6.70–86.03% (Er3), and 4.81–85.75% (Er4) intervals. The data mentioned above verify that photon absorption in the Er glass samples reaches its highest level during the

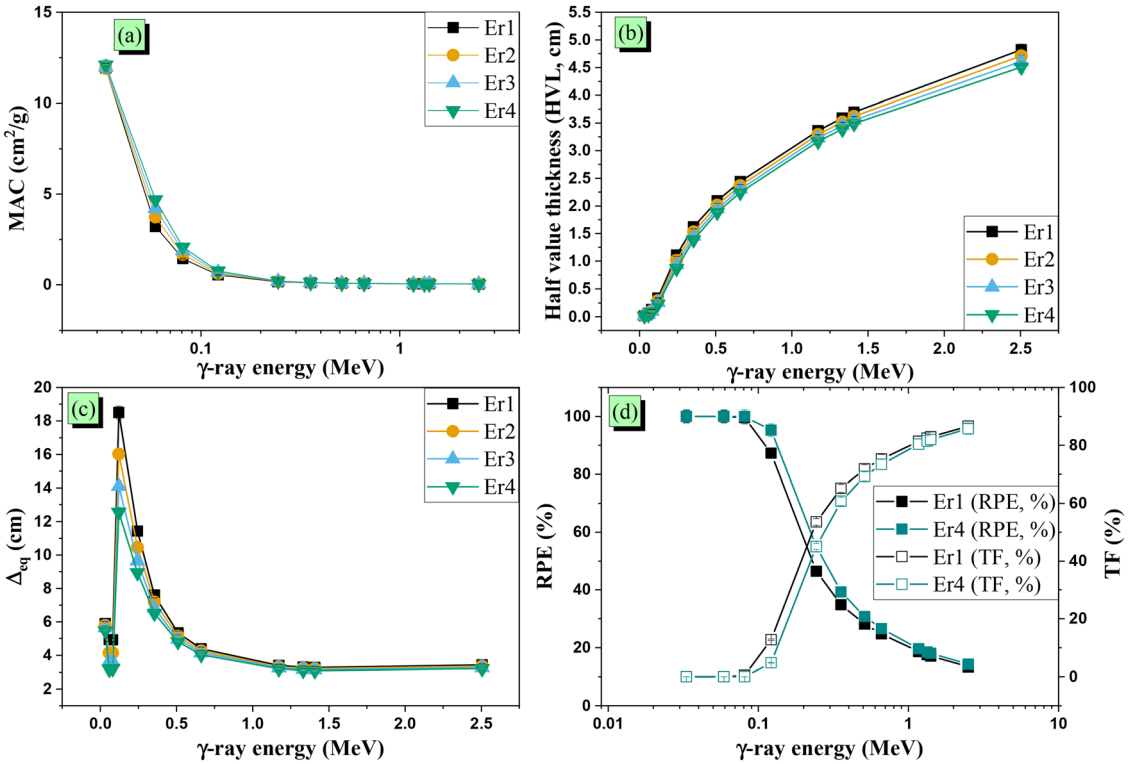

Fig. 12 The γ-ray energy's influence on (a) mass attenuation coefficient ($cm^2\ g^{-1}$), (b) half-value thickness (cm), (c) sample thickness equivalent to 1 cm of lead (Δ_{eq}, cm), and (d) radiation protection efficiency (RPE, %) and transmission factor (TF, %) for the prepared Er glass samples.

PE interaction, whereas photon transmission falls to its minimum levels. As a result, the TFs are less than 1% in the $E_\gamma \leq 0.081$ MeV energy interval. Subsequently, as the likelihood of PE reduced and the CS contacts grew, photon transmission exceeded photon absorption, resulting in a rise in the transmission ratio and TFs. Fig. 12(d) displays also the high percentage of RPEs at low energy interval (PE interval), where the RPEs decrease throughout 100.00–87.25%, 100.00–90.73%, 100.00–93.30%, and 100.00–95.19%, respectively, for the Er1, Er2, Er3, and Er4 samples at 1 cm thickness. This is due to a 0.0332 to 0.122 MeV γ-ray energy increase. Because of the decrease in (I_a) photons, these high RPEs for the prepared Er samples dramatically dropped with rising γ-photon energy over the CS interval. With a γ-ray energy increase to 2.506 MeV, the RPEs for a 1 cm thickness of the Er1, Er2, Er3, and Er4 glass samples decreased to 13.39%, 13.68%, 13.97%, and 14.25%, respectively, as illustrated in Fig. 12(d).

Eqn (10) states that Δ_{eq} is a comparison of photon transmission for the prepared Er samples and pure lead element. The large reduction in the LACs for both lead and the prepared Er samples is responsible for the Δ_{eq} values' high reduction at low energy intervals, as seen in Fig. 12(c). For instance, the LAC for Pb reduced by 85.54% with a γ-ray energy increase over the PE period (*i.e.*, $0.0332 < E_\gamma \leq 0.122$), but the LACs for the prepared glass samples Er1, Er2, Er3, and Er4 declined by 95.39%, 94.78%, 94.22%, and 93.70%, respectively. With a 0.0332 to 0.081 MeV γ-ray energy increase, the Δ_{eq} values decreased throughout 5.892–4.920, 5.787–4.143 cm, 5.639–3.613, and 5.474–3.212 cm for the Er1, Er2, Er3, and Er4 glass samples, respectively, due to the high declination of LACs for the prepared glasses compared to that of pure lead. Because of the Pb's K-edges, the largest values of Δ_{eq} were observed at 0.122 MeV, where they reached 18.500, 16.023, 14.100, and 12.560 cm for glass samples Er1, Er2, Er3, and Er4, respectively. The reduction in LAC for lead (93.09%) during the CS interval is more than that seen in the investigated glass samples, whereas the decreases in LACs of the Er1, Er2, Er3, and Er4 glass samples are 76.98%, 78.44%, 79.68%, and 80.73%, respectively. The prepared Er glasses' moderate reduction in LACs results in a corresponding moderate reduction in Δ_{eq} values within the CS interval. The Δ_{eq} values were altered throughout the ranges of 11.422–3.427, 10.453–3.349, 9.633–3.275, and 8.938–3.205 cm for the ER1, Er2, Er3, and Er4 glass samples, respectively, due to the γ-ray energy increase within the 0.244–2.506 MeV interval.

As seen in Fig. 13(a)–(d), the produced samples' radiation shielding properties are impacted by an increase in Er_2O_3 concentration, contingent upon the Er glass samples' chemical composition. The manufactured Er glass samples' density increases with increasing Er_2O_3 concentration between 1.25 and 5 mol%, reaching 3.750 and 3.982 g cm^{-3}, respectively. When the manufactured glass samples' Er_2O_3 concentration replaced those of B_2O_3, the electron density and effective atomic number (Z_{eff}) increased.[69,70] This led to a rise in sample density. The efficiency of the prepared glasses' radiation shielding was investigated at PE and SC intervals, as previously demonstrated. For both PE and CS interactions, the photon cross-section of interaction is proportional to *Z*eff4.6

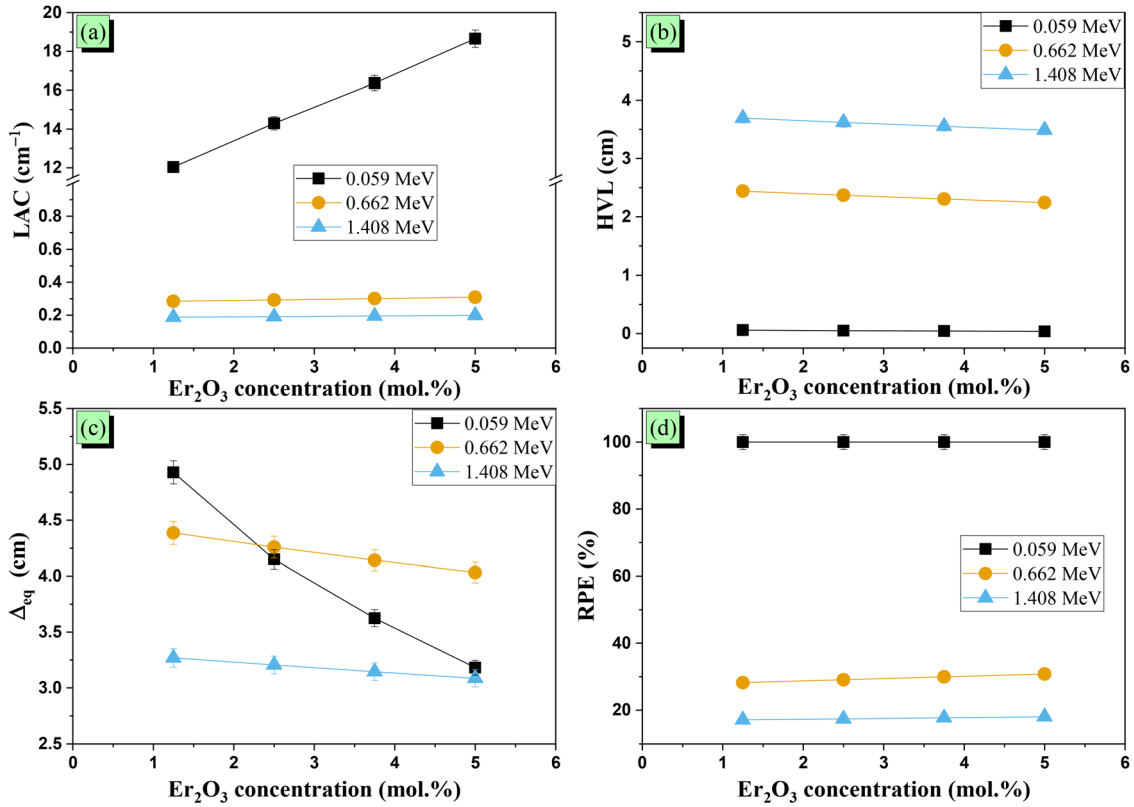

Fig. 13 Variation of (a) LAC (cm^{-1}), (b) half-value thickness (HVL, cm), (c) sample thickness equivalent to 1 cm of lead (Δ_{eq}, cm), and (d) RPE (%) *versus* the Er_2O_3 concentrations in the prepared glass samples.

and Z_{eff}, respectively, over these two intervals. Therefore, the rise in the Z_{eff} greatly boosts the radiation shielding properties in the PE interval, although a minor enhancement was found across the CS interval. When the Er_2O_3 concentrations rose between 1.25 and 5 mol%, Fig. 13(a) indicates an enhancement in the LACs by 54.94%, 8.78%, and 5.93%, respectively, at 0.059, 0.662, and 1.408 MeV. For the prepared glass samples, there is a decrease in the necessary HVLs and (I_t) photons after a LAC increase. As Fig. 13(b) illustrates, an Er_2O_3 concentration increase between 1.25 and 5.00 mol% reduces the HVLs at 0.059, 0.662, and 2.506 MeV in the 0.058–0.037, 2.439–2.243, and 4.822–4.509 cm ranges, respectively. There is (I_a) photon growth along with the aforementioned (I_t) photon reduction. Consequently, as the Er_2O_3 level was raised, the RPEs of the produced glass

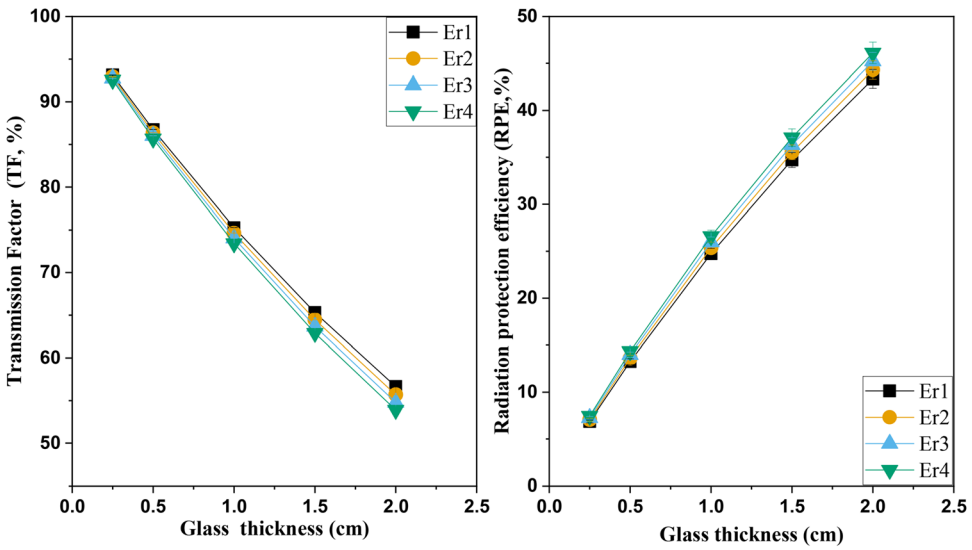

Fig. 14 Variation of (a) TF (%) and (b) RPE (%) *versus* the glass thickness at 0.662 MeV.

samples increased in certain intervals, as Fig. 13(d) shows at 24.74–26.59% (0.662 MeV) and 13.39–14.25% (2.506 MeV) as the Er_2O_3 level increases from 1.25 to 5.00 mol%. At 0.059 MeV, the RPEs of every sample are almost 100%. Furthermore, the manufactured Er glass samples' Δ_{eq} is decreased by the rise in μ values brought on by the increased Er_2O_3 content. Fig. 13(c) shows the Δ_{eq} values to drop over 4.928–3.181 cm (0.059 MeV), 4.386–4.032 cm (0.662 MeV), and 3.427–3.205 cm (2.506 MeV) with an increase in the Er_2O_3 concentration between 1.25 and 5.00 mol%.

As shown in Fig. 14(a) and (b), the produced samples Er1, Er2, Er3, and Er4 have RPEs that grow with a 0.25 to 2 cm thickness increase, decreasing the TFs dramatically. Within the samples, the γ-photon–electron interaction probability increases with increased sample thickness. For every sample under investigation, this rise in the interaction probability results in a (I_a/I_o) ratio increase and a (I_t/I_o) ratio decrease. As seen in Fig. 14(a), this decline in the (I_t/I_o) ratios caused a drop in the TFs for every sample that was examined. The Er1, Er2, Er3, and Er4 prepared samples' TF values decrease with a 0.25 to 2 cm glass thickness increase at 93.14–56.65%, 92.95–55.70%, 92.75–54.78%, and 92.56–53.89%, respectively. As demonstrated in Fig. 14(b), in contrast, with a 0.25 to 2 cm glass thickness increase, the RPEs increased over the interval of 6.857–43.352%, 7.055–44.305%, 7.247–45.219%, and 7.436–46.108%, respectively, for the prepared glass samples Er1, Er2, Er3, and Er4.

4. Conclusion

In summary,

• A group of four transparent pink bulk glasses were successfully fabricated *via* melting and later annealing with the composition formula of $(TeO_2)_{20}(GeO_2)_{10}(B_2O_3)_{35-x}(MgO)_{35}(Er_2O_3)_x$ with x values of 1.25, 2.5, 3.75, and 5, which represents the erbium oxide concentration.

• The XRD profile provides confirmation of the glass's random structure, confirming the amorphous structure with a broad band at 28 and 50 degrees.

• The absorption spectra for glass samples doped with different Er_2O_3 concentrations show nine absorption bands related to the ground state ($^4I_{15/2}$) to different excited state ($4G_{11/2}$, $4G(1)_{9/2}$, $4F_{3/2}$–$4F_{5/2}$, $4F_{7/2}$, $2H_{11/2}$, $4S_{3/2}$, $4F_{9/2}$, $4I_{9/2}$, and $4I_{11/2}$) transitions, which correspond to 378, 407, 450, 488, 523, 543, 652, 794, and 977 nm.

• The adding of Er_2O_3 to the glass system reduced the band gap (E_g) values, which ranged from 3.553, to 3.516 eV, respectively. The E_U values increased gradually by replacing B_2O_3 with Er_2O_3, and their values are 0.266, 0.268, 0.277, and 0.278 eV for Er1, Er2, Er3, and Er4.

• The dissociation energy for the glass samples was reduced from 17.270 to 17.236 kcal cm^{-3} for the Er1 and Er4 samples due to a strong bond (B_2O_3) being replaced with a weak one (Er_2O_3). This result led to a reduction in the elastic moduli by adding Er_2O_3 to the glass system.

• Regarding the γ-ray protection capacity, it is increased with the prepared boro-tellurite glasses' increased Er_2O_3 content. The enrichment in the Er_2O_3 concentration in the range of 1.25–5 mol% raises the prepared samples' LAC within the ranges of 0.624–0.798 cm^{-1} (0.244 MeV), 0.331–0.368 cm^{-1} (0.662 MeV), 0.206–0.219 cm^{-1} (1.173 MeV), and 0.144–0.154 cm^{-1} (2.506 MeV). The LAC increase reduces the required half-value thickness by 35.46%, 21.75%, 9.98%, and 6.49%, respectively, at 0.059, 0.244, 0.511, and 2.506 MeV. Furthermore, Er_2O_3 addition up to 5 mol% increases the RPE for 1 cm thickness of the prepared samples to 26.6% at 0.662 MeV. After that, the aforementioned RPE further increased to 46.10% when the prepared glass thickness was raised to 2 cm.

• The main finding of the manuscript is that Er_2O_3 addition to Germanium boro-tellurite glasses slightly reduced the prepared glasses' optical and mechanical properties. On the other hand, radiation protective properties were enhanced, making them a good lead-free alternative material for radiation protective applications.

Author contributions

KAM, MIS, KAM, MHAM, IAJ, SDK: conceptualization, methodology, software, validation, investigation, data curation, writing – review and editing, visualization, supervision.

Conflicts of interest

The authors declare that they have no conflict of interest.

Data availability

The data that support the findings of this study will be available upon request.

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