Nuclear Engineering and Technology 54 (2022) 4708–4714

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Radiation parameterizations and optical characterizations for glass shielding composed of SLS waste glass and lead-free materials

Thair Hussein Khazaalah [a,*], Iskandar Shahrim Mustafa [a,**], M.I. Sayyed [b]

[a] School of Physics,Universiti Sains Malaysia, 11800, USM, Penang, Malaysia
[b] Department of Physics, Faculty of Science, Isra University, Amman, Jordan

A R T I C L E I N F O

Article history:
Received 17 May 2022
Received in revised form
7 August 2022
Accepted 10 August 2022
Available online 23 August 2022

Keywords:
Soda lime silica glass SLS waste
Half value layer
Linear attenuation coefficient
Optical properties
Refractive index
Lead free glass shielding

A B S T R A C T

The novelty in the present search, the Soda-Lime-Silica (SLS) glass waste to prepare free lead glass shielding was used in order to limit the accumulation of glass waste, which requires extensive time to decompose. This also saves on the consumption of pure SiO_2, which is a finite resource. Furthermore, the combining of BaO with Bi_2O_3 into a glass network leads to increased optical properties and improved attenuation. The UV–Visible Spectrophotometer was used to investigate the optical properties and the radiation shielding properties were reported for current glass samples utilizing the PhysX/PDS online software. The optical property results indicate that when BaO content increases in glass structure, the Urbach energy ΔE, and refractive index n increases while the energy optical band gap E_{opt} decreases. The result of the metallisation criteria (M) revealed that the present glass samples are nonmetallic (insulators). Furthermore, the radiation shielding parameter findings suggest that when BaO was increased in the glass structure, the linear attenuation coefficient and effective atomic number (Z_{eff}) rose. But the half-value layer HVL declined as the BaO concentration grew. According to the research, the glass samples are non-toxic, transparent to visible light, and efficient radiation shielding materials. The Ba5 sample is considered the best among all the samples due to its higher attenuation value and lower HVL and MFP values, which make it a suitable candidate as transparent glass shield shielding.

1. Introduction

Nuclear applications are becoming more prevalent in our daily lives as a because of their many advantages. They are employed in many fields, such as industry, agriculture, medicine, and radiology, and are used to generate clean energy instead of fossil fuels. However, there are a lot of critical side effects for patients and employees exposed to radiation when they are exposed to high doses of radiation, particularly ionizing radiation, such as DNA damage and mutations. This leads to an increased risk of cancer. In addition, when the lens of the eye is exposed to a high radiation dose, it will cause vision loss because of corneal opacity. As a result, men and women who get a lot of ionizing radiation in their bodies will become sterile [1–5].

Researchers in the shielding field are interested in developing shielding materials that will help limit the hazards of radiation. Lead, concrete, ceramics, and polymers are some of the best shielding materials because they can reduce the amount of radiation that gets through them, but there are some disadvantages to their use, like that they are opaque [6–8], and [9]. Glass is a suitable alternative to opaque shielding materials due to its several attractive features, such as nontoxicity, being cheap, being able to be modified by adding heavy metal oxide, and the ability to let light pass through [10–12]. Researchers working on glass shielding materials focused on using heavy metal oxides, particularly eco-friendly metal oxides such as Bi_2O_3, BaO, and others, as a modifier in the glass structure to improve the ability of glass to absorb and attenuate radiation due to the fact that these materials are very dense, have a high effective atomic number, a high refractive index, long infrared transmission, and are not toxic. Bi_2O_3 has high optical basicity, large polarizability, and large optical susceptibility values [13,14]. However, if more than 25% Bi_2O_3 is used in the glass network, the colour turns dark brown or black [10,15]. The presence of zinc oxide (ZnO) significantly affects the capacity for glass production and slows the pace of crystallisation across the glass network. El-Denglawey et al. [16] measured the linear and mass

* Corresponding author.
** Corresponding author.
E-mail addresses: khazaalah@yahoo.com (T.H. Khazaalah), iskandarshah@usm.my (I.S. Mustafa).

https://doi.org/10.1016/j.net.2022.08.009
1738-5733/

attenuation coefficients and other shielding parameters of glass containing bismuth using Monte Carlo simulation and the XCOM program. They found that the LAC and MAC values decreased as photon energy was increased. Furthermore, Ahmad et al. [17] investigated the radiation shielding properties of bismuth and lead doped into SLS glasses experimentally at energies of 0.059, 0.122, and 0.662 MeV. They discovered that the linear and mass attenuation coefficients decreased as gamma energy increased. The results are consistent with a number of studies which are [18–20], and [21].

Soda lime silica (SLS) glass is one of the types of glass with a higher than 80% production rate in fields such as windows, tableware, containers, and flat glass. It has significant properties compared to other conventional glass due to its unique properties, such as good glass-forming nature, good electrical resistivity, and low production costs [22]. On the other hand, there are some issues associated with the accumulation of glass waste, which takes a long time to decompose. To tackle the environmental problem, researchers are focusing on reusing waste glass in other industries. Kurtulus. et al. [23] and kurtulus et al. [22] employed the SLS glass waste with variable concentrations of SrO and MoO_3 in order to make glasses shielded against radiation. Malidarre et al. [24] fabricated glass shielding material from SLS glass waste with Sb_2O_3. Ahmad et al. [17] used the SLS glass waste as an alternating source of SiO_2 to prepare two glass systems against radiation; Bi_2O_3-ZnO-B_2O_3-SLS and PbO-ZnO-B_2O_3-SLS.

The present work aims to first develop glass shielding materials against radiation by using non-toxic materials and the SLS waste glass as an alternative to SiO_2 in order to reduce production costs, save natural resources, and limit waste accumulation. The second aim is to treat the brown dark of bismuth glass. The third aim is to compute the shielding parameters theoretically in the energy range of (0.015–15) MeV employing PhyX/PSD such as LAC, HVL, and Z_{eff}. The fourth goal is to calculate optical parameters such as the energy gap in two transition cases: direct and indirect, as well as ΔE, n, RL, and T.

2. Materials and method

2.1. Glass samples preparation

In our recent paper, we reported the structural properties for these glasses and we experimentally measured some of the radiation shielding parameters for these glasses. We used only three photon energies (i.e. 59.54, 662, and 1333 keV). While, in the current work, we extended our previous work and studied the optical properties for the prepared glasses and we selected wide energy range (0.015–15 MeV) and examined the radiation shielding properties for these glasses by theoretical approach (i.e, Phy-X software) in order to understand the attenuation features of these glasses at low, moderate and high energy range [25]. The Soda Lime Silica (SLS) glass wastes were used to produce silicon dioxide (SiO_2). As mentioned in the previous study [25], SLS has a SiO_2 content of 74.1% and other elements. Fig. 1 offered the steps of fabrication of the present glass samples. In the first step, the SLS waste was crushed to become powder, and then the chemical materials, which are detailed in Table 1, were mixed and moved from an agate mortar to an alumina crucible. In the second step, the mixed materials were melted in the furnace at 1200 °C for 1.5 h. After that, in the heated brass cylinder, the molten liquid was poured to start the annealing process in the oven at 350 °C for 2 h. In the last step, the glass samples were cooled to room temperature and polished. The composition used to fabricate glass samples was (x) BaO (1-x)[0.3 ZnO 0.2 Bi_2O_3 0.2 B_2O_3 0.3 SLS] (where x are 0.01, 0.02, 0.03, 0.04, and 0.05 mol). Glass samples thickness is 6 mm.

The radiation shielding parameters of prepared glass samples were computed theoretically by employing Phys-X/SPD software in the energy range of (0.015–15) MeV to investigate the ability of the current glass samples to attenuate the radiation. The radiation parameter formulas were explained in previous literature [26]. The optical absorbance (A) of present glass samples was measured utilizing a UV–Visible Spectrophotometer in the wavelength range of 200–800 nm at room temperature. The optical absorption coefficient ($\alpha(\nu)$) was calculated using Eq.(1). The other optical

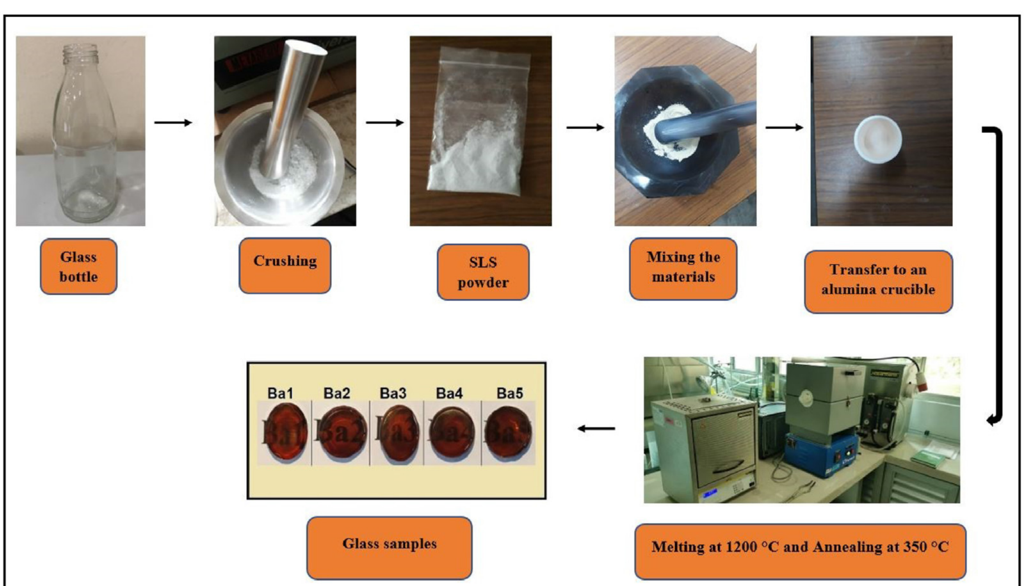

Fig. 1. Steps in preparation of glass samples.

Table 1
Compositions, ρ, and V_m of the present glass samples.

Sample	Composition (mole fraction %)					P (gcm^{-3})	V_m (cm^3mol^{-1})
	Bi_2O_3	ZnO	B_2O_3	SLS	BaO		
Ba1	19.8	29.7	19.8	29.7	1	5.157	29.01
Ba2	19.6	29.4	19.6	29.4	2	5.161	28.99
Ba3	19.4	29.1	19.4	29.1	3	5.221	28.67
Ba4	19.2	28.8	19.2	28.8	4	5.249	28.52
Ba5	19	28.5	19	28.5	5	5.256	28.49

properties of glass samples were calculated based on the absorption values (d), and the formulas for them are shown in Table 2 [27].

$$\alpha(\nu) = 2.303\left(\frac{A}{d}\right) \quad (1)$$

3. Results and discussion

3.1. The radiation shielding analysis

The linear attenuation coefficient (LAC) of fabricated glass samples was investigated utilizing online Phy-X/PSD software. The LAC was dramatically reduced as photon energy rose in the low energy zone dominated by the photoelectric effect, as seen in Fig. 2. As energy increased in the medium and high energy zones dominated by the compton effect and pair production, the LAC decreased. Fig. 3 illustrates the relationship between LAC and BaO concentration in fabricated glass samples at various energies. When the BaO content in glass samples was increased, the LAC values rose significantly in low energy areas, but the LAC values stayed about the same in other energy areas [25].

As can be seen in Fig. 4, the HVL of the current glass samples was calculated vs energy. According to the findings, HVL rose with increasing photon energy, but decreased with increasing BaO concentration. The HVL value for the Ba5 sample is lower than for the other samples. Fig. 5 compares the HVL results of present glass samples with other studies that have been published. It can be mentioned that the HVL values in the present study were lower than the HVL results in the previous studies [28–31].

The effective atomic number (Z_{eff}) parameter may be used to explain radiation attenuation in complex media. The Z_{eff} values were investigated in relation to photon energy, as shown in Fig. 6. The results displayed that the Z_{eff} values lowered in the energy

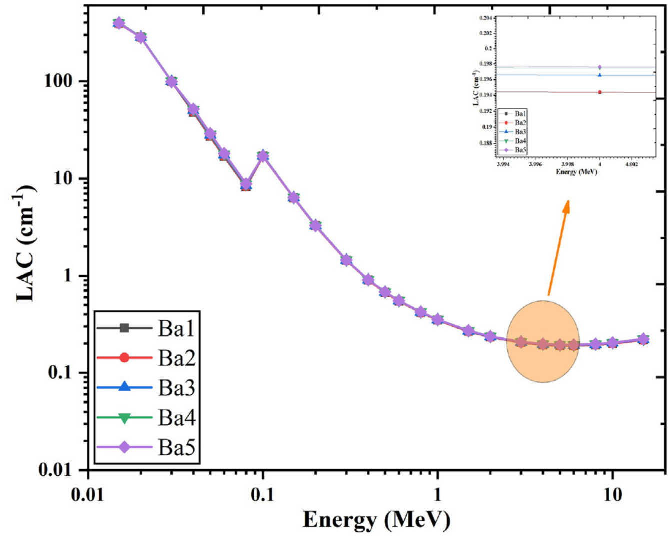

Fig. 2. The linear attenuation coefficient (LAC) of fabricated glass samples against energy.

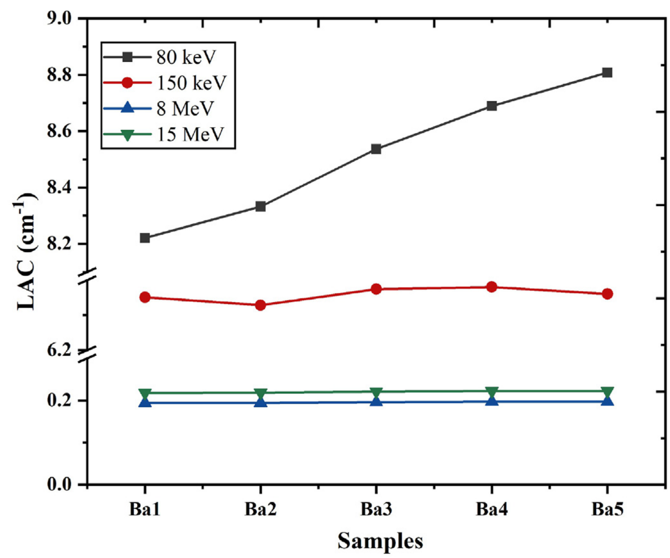

Fig. 3. The LAC of present glass samples against BaO concentration.

Table 2
The optical parameters of the fabricated glass samples.

Parameters	Equation	Samples					Reff
		Ba1	Ba2	Ba3	Ba4	Ba5	
Indirect bandgap	$\alpha(\nu) = \frac{B(h\nu - E_{opt})^n}{h\nu}$	1.75	1.74	1.73	1.71	1.68	[33]
Direct bandgap		2.28	2.27	2.26	2.24	2.23	
Urbach energy (ΔE)	$\alpha(\nu) = B\exp\left(\frac{h\nu}{\Delta E}\right)$	0.383	0.388	0.391	0.392	0.448	[34]
Refractive index (n)	$\frac{n^2-1}{n^2+2} = 1-\sqrt{\frac{E_{opt}}{20}}$	2.853	2.858	2.864	2.874	2.890	[35]
Molar refractive indesx Rm	$R_m = \left[\frac{n^2-1}{n^2+2}\right]V_m$	20.432	20.448	20.475	20.499	20.504	[36]
Metallisation criterion (M)	$M = 1-\frac{R_m}{V_m}$	0.296	0.295	0.294	0.292	0.290	[37]
Reflection loss RL	$R_L = \left(\frac{n-1}{n+1}\right)^2$	0.295	0.296	0.298	0.300	0.303	[5]
Transmition (T)	$T = \frac{2n}{n^2+1}$	0.544	0.543	0.541	0.539	0.535	[38]

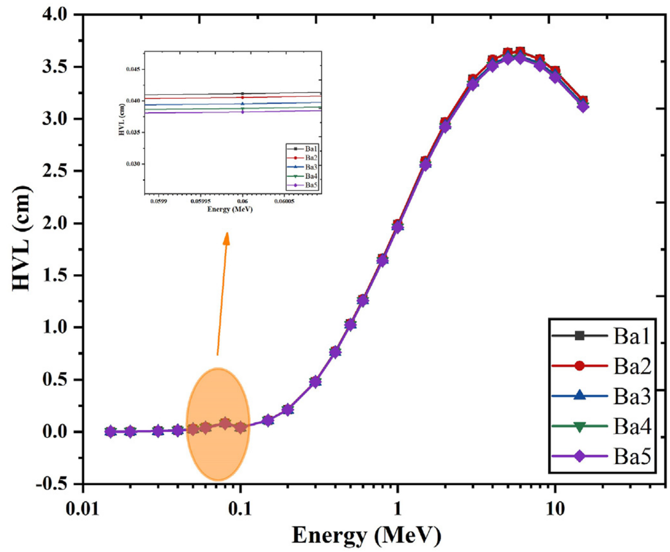

Fig. 4. The half value layer of fabricated glass samples against energy.

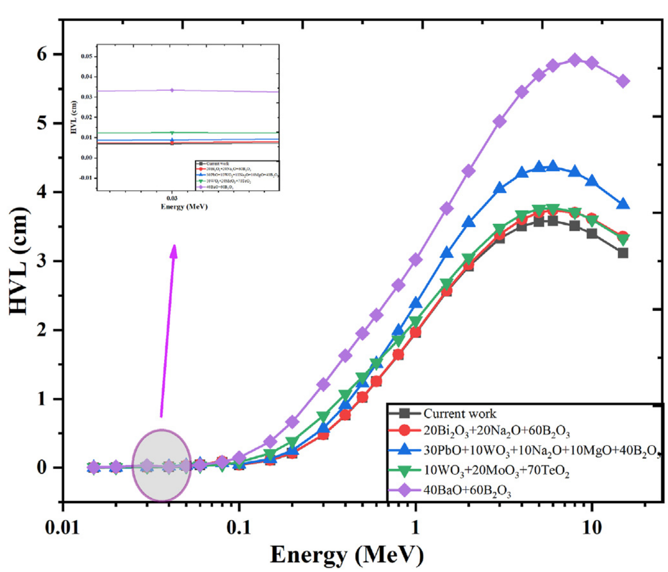

Fig. 5. The comparison of the HVL results of current work with previous studies.

range between (20–80) keV, then elevated to their maximum value at 100 keV. Due to the photoelectric effect, which is prominent in this energy range and is inversely proportional to $E^{3.5}$. The Z_{eff} is quickly reduced in the Compton region, which extends from 150 keV to 1 MeV. At above 1.5 MeV, the Z_{eff} was slightly increased with photon energy due to pair production dominating. Fig. 7 illustrates the relationship between Z_{eff} and BaO concentration. The result showed that increases in the amount of BaO made Z_{eff} values drop a little in the photoelectric regions, but in the pair production and compton regions, they went up [32].

3.2. The optical analysis

The optical absorption spectra of the BaO doped glass network were measured and referred to in Fig. 8 within the wavelength range of 200–800 nm. The results indicate that in the UV region, the absorption was very strong and the absorption edge was not a sharp peak. This indicates that the glass network is in an amorphous state. This result corresponds with the XRD analysis in

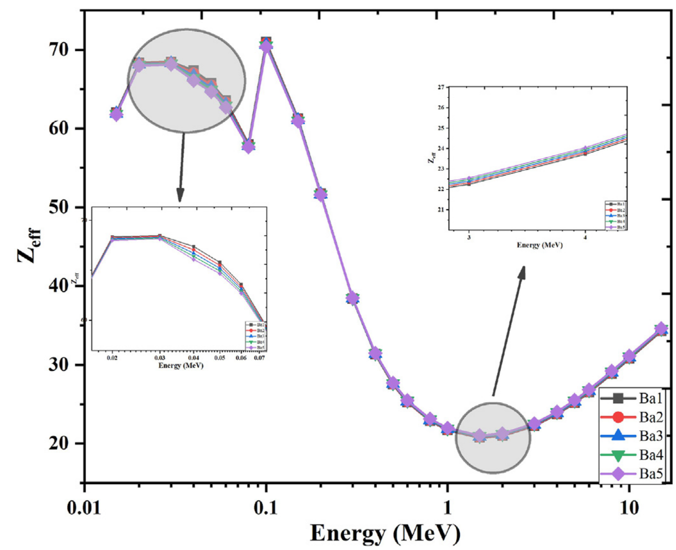

Fig. 6. The effective atomic number of fabricated glass samples against energy.

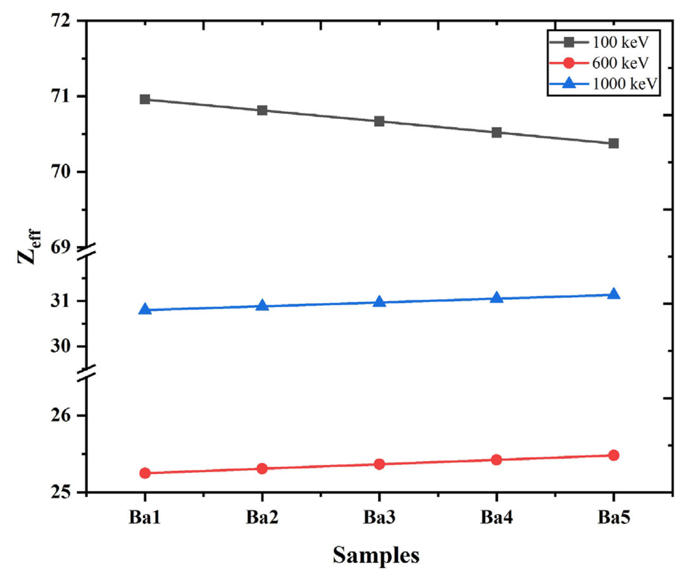

Fig. 7. The effective atomic number of fabricated glass samples versus BaO content.

previous research (see Fig. 9) [25]. Furthermore, the absorption edge was slightly transferred toward a higher wavelength when increasing the BaO content in glass samples due to the glass rigidity decreasing [34,39]. Fig. 10 displays the energy optical bandgap (E_{opt}) for direct and indirect transitions of the synthesized glass samples. The E_{opt} values were reduced for both direct and indirect transitions when the BaO concentration was increased. It can be seen that the E_{opt} for direct transition was larger than for indirect transition. Due to the BaO modifier, the glass network has become less ordered, increasing the number of non-bridging oxygen atoms [27].

The absorption edges frequently follow the Urbach rule (ΔE) of amorphous materials because of the disordered structures. Table 2 displays the ΔE values of the present glass samples, which increase from 0.383 to 0.448 eV. This result shows an increasing number of defects. BaO in the glass network converts the weak bonds to defects. Therefore, the glass network stability is reduced [40,41]. The refractive index (n) based on the indirect optical band gap for current glass samples is reported in Table 1. The n values were increased from 2.853 to 2.889. The refractive index and the optical

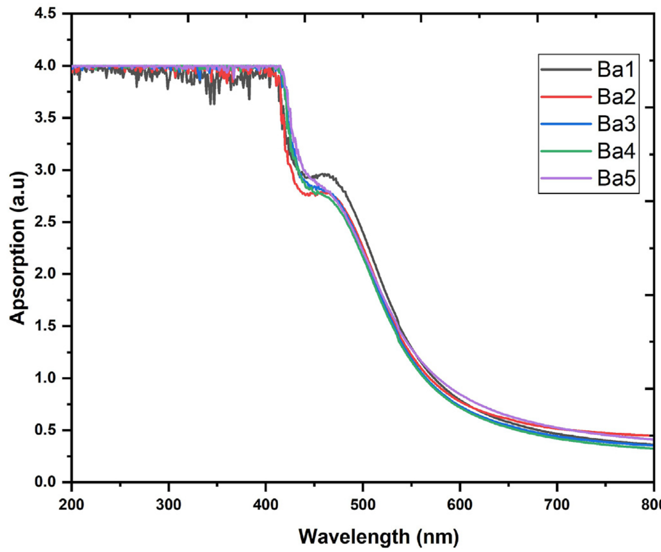

Fig. 8. UV-VIS absorption spectra for prepared glass samples.

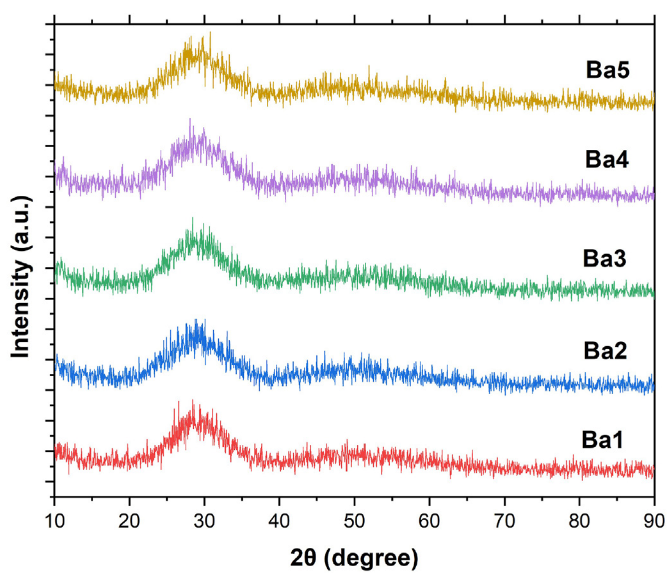

Fig. 9. XRD patterns of BaBiZnB-SLS glass samples [25].

band gap energy have an inverse relationship as illustrated in Fig. 11. The molar refraction (R_m) was calculated and the results are shown in Table 2. R_m values were increased from 20.43 to 20.50 cm^3/mol as the BaO concentration rose as a result of the formation of non-bridging oxygen and the glass structure was altered [42]. The metallisation criterion (M) of the present samples was measured. The M results were less than 1, positive, and were lowered from 0.296 to 0.290 as BaO content was increased. This indicates that the present glass samples are insulators (non-metallic). It can be explained using Herzfeld's suggestion in the Metallisation of Condensed Matter Theory. He proposed that in the Lorentz-Lorenz equations, the refractive index becomes infinite when $R_m/V_m = 1$. If the glass materials have a condition $R_m/V_m \geq 1$, they will have mobile electrons, and glass materials are predicted to be metallic. However, the glass materials are predicted to be an insulator if $R_m/V_m < 1$ [43,44]. Fig. 12 displays the relationship between reflection loss (RL) and transmission (T) of the fabricated

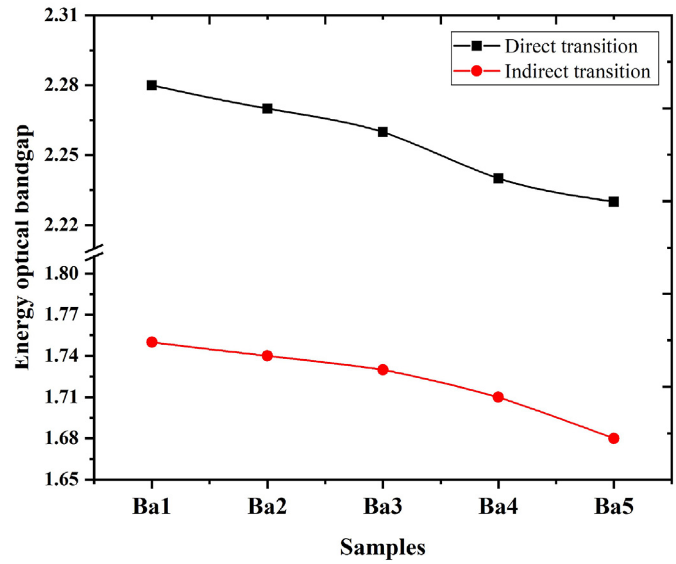

Fig. 10. Direct and indirect band gaps of the synthesized glass samples.

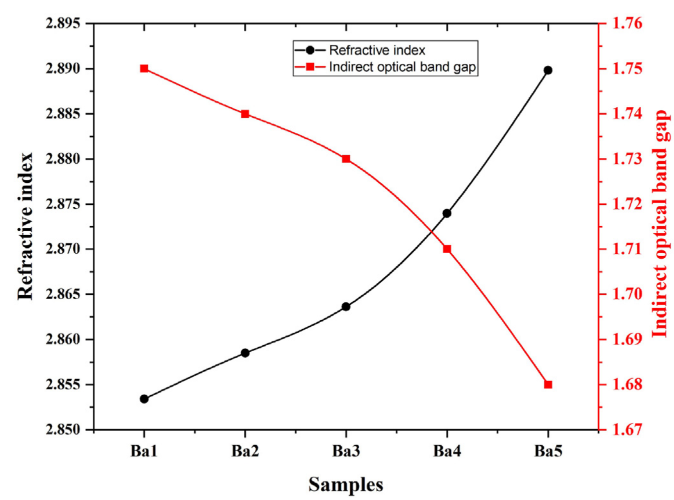

Fig. 11. Refractive index and indirect optical band gap of the synthesized glass samples.

glass samples. It can be noticed that the relationship between RL and T is inversed as BaO content is increased.

3.2.1Conclusion

The melt quenching process was used to create five glass samples that can be used to protect against radiation. The glass composition was (x) BaO (1-x) [0.2 B_2O_3 0.3 SLS 0.3 ZnO 0.2 Bi_2O_3]. SLS waste glass, which included 74.1% of SiO_2 and other contents, was employed in glass shielding as an alternate supply of silicon dioxide. The radiation parameter results showed that as the photon energy was increased, the linear attenuation coefficient values and the effective atomic number values decreased while the half value layer were raised. The HVL value of a Ba5 sample is lower than that of the prepared glass samples and heavy metal glasses, which have been published. The optical properties results indicate that when the BaO concentration was raised, the E_{opt} values decreased in both cases: direct and indirect, while the refractive index values increased from 2.853 to 2.890 and the Urbach values raised from 0.383 to 0.448. Based on these findings,it is possible to conclude

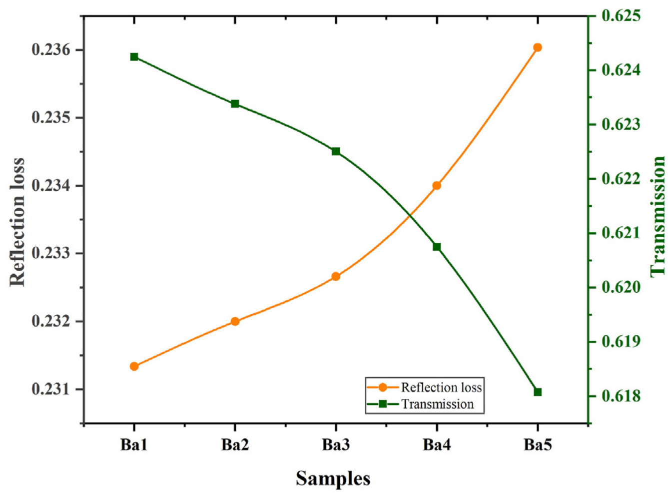

Fig. 12. Reflection loss and transmission of the synthesized glass samples.

that the current glass can be used as a radiation shielding material due to its achieving the desirable properties of a glass shield: being nontoxic, passing visible light well, and attenuating radiation in the different energy regions. Also, using SLS glass waste saves natural minerals such as pure SiO_2 and reduces the accumulation of the amount of glass waste that takes a long time to decompose.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors appreciate Universiti Sains Malaysia (USM) for the research facilities. Appreciation also goes to the Ministry of Higher Education, Malaysia, for the financial support towards this research under the Fundamental Research Grant Scheme with project code FRGS/1/2019/STG07/USM/02/19 and project ID 17443 (203/PFIZIK/6711769).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2022.08.009.

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