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Effects of Gamma Irradiation on the AC Electrical Properties of Cross-Linked Epoxy Resin/Bisphenol A-Based Polycarbonate Composites

Ziad Alqudah [1,*], Hassan K. Juwhari [2] and Ziad Elimat [3]

[1] Jordan Atomic Energy Commission, Amman 11934, Jordan
[2] Physics Department, University of Jordan, Amman 11942, Jordan
[3] Department of Scientific Basic Sciences, Faculty of Engineering Technology, Al-Balqa' Applied University, Al-Salt 19117, Jordan
* Correspondence: zyad.alqudah@jaec.gov.jo

Abstract: The effects of gamma radiation on the AC electrical properties of highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples have been investigated as a function of concentrations of bisphenol A-based polycarbonate, frequency, and temperature. The composite samples contained different bisphenol A-based polycarbonate concentrations of 0, 4, 8, 10, and 15 by wt%. The gamma irradiation process was performed at different gamma doses of 0, 100, 300, and 500 Gy. The AC electrical properties of the tested samples were studied before and after gamma irradiation within a frequency range of 200 kHz to 1 MHz. The results show that after irradiation, a consistent decrease in complex impedance values (Z^*) was observed, indicating an increase in conductivity due to radiation-induced scission of the composite structure. Dielectric properties, including the dielectric constant (ε_r) and dielectric loss (ε_i), exhibited an increase with higher doses and higher polycarbonate concentrations, signifying the formation of defect sites and charge carrier trapping. AC electrical conductivity (σ_{ac}) displayed a notable rise post irradiation, with temperatures ranging from 30 °C to 110 °C, and higher radiation doses and higher temperatures led to increased conductivity. The activation energy (E_a) decreased as the radiation dose increased, reflecting structural modifications induced by radiation.

Keywords: epoxy; bisphenol A-based polycarbonate; gamma radiation; AC electrical; conductivity

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1. Introduction

In recent years, the exposure of polymeric composites to gamma radiation has gained considerable attention from numerous researchers due to their significance in industrial and technical applications to enhance and improve various physical properties, including optical and electrical properties [1–4].

The gamma irradiation technique has been employed by researchers since it is well-known to be one of the most highly effective ways to enhance the physical and chemical properties of polymeric composites [5,6].

The published scientific research in the literature indicates that gamma radiation has a profound impact on the physical and chemical properties of polymer composites. These effects include structural modifications, scission or cross-linking, alterations in the degree of filler particle aggregation, the formation of holes, changes in the band gap value, and the generation of more radicals and electric dipoles, as has been extensively documented in studies [7–15].

In a related study [16], the focus was directed towards evaluating the influence of varying gamma irradiation doses on a composite material composed of polycarbonate and polybutylene terephthalate. Their investigation yielded noteworthy findings, notably a reduction in the band gap energy, which consequently led to an increase in electrical

conductivity. This enhancement in electrical conductivity was attributed to structural and optical modifications induced by the gamma irradiation process. Expanding on this theme, the research in [17] delved into the impact of gamma irradiation on nanocomposite films consisting of polycaprolactone and zinc oxide. Intriguingly, their findings suggested that the structural properties of the irradiated samples remained largely unaltered even when exposed to a substantial gamma dose of 25 kGy. In a parallel line of inquiry presented in [18], the effects of gamma irradiation on film samples crafted from polycarbonate, specifically Makrofol-E, were explored across a wide spectrum of gamma doses, ranging from 10 kGy to 200 kGy. Their results uncovered a remarkable enhancement in the radiation resistance of Makrofol-E, rendering it exceptionally suitable for applications within the medical product industry. Notably, prior investigations, as in [19], have primarily focused on examining the impact of temperature variations between 25 °C and 100 °C, as well as exploring a frequency range spanning from 10 Hz to 10^6 Hz. The study referenced in work [20] demonstrated that gamma irradiation causes notable modifications to the electrical properties of epoxy resin, impacting both its thermally stimulated discharge behavior and DC conductivity, and these alterations are associated with degradation and cross-linking processes. In the study referenced in [21], gamma irradiation of epoxy–lead oxide composites led to changes in chemical structure, surface morphology, and mechanical properties, along with reduced thermal stability at higher gamma doses, while the gamma attenuation properties and XRD spectrum remained unaffected even under significant irradiation. The study [22] explored how gamma radiation impacts thin epoxy resin films. XRD analysis revealed structural changes with varying film thickness and gamma doses ranging from 0 to 120 kGy. It showed a shift from amorphous to crystalline phases at lower thicknesses and higher radiation doses, enhanced by the hardened material. SEM confirmed this improved crystal morphology and uniform microstructure.

In our previous work [23], we studied epoxy–alumina (Al_2O_3) composites, particularly their AC electrical and optical properties. It was found that their AC electrical conductivity and dielectric behavior are influenced by both the applied frequency and alumina concentration. Additionally, optical properties, including the absorption coefficient and localized state width, varied with alumina concentration.

The main goal of this work is to study the effects of gamma irradiation on the AC electrical properties and parameters of highly cross-linked epoxy resin as a filled matrix with different concentrations of bisphenol A-based polycarbonate by exposing them to different gamma radiation doses, in order to enhance their electrical conductivity.

2. Materials and Methods

2.1. Samples Preparation

The samples in this study were prepared at the C.N.R. laboratories in Naples, Italy, following the procedure outlined in reference [19]; 20 g of polycarbonate with a number-average molecular weight of 12×10^3 and a weight-average molecular weight of 31×10^3 was carefully dissolved in 39.6 g of epoxy resin, specifically Novolac DEN 438. This dissolution process extended over a 5 h period and was carried out at a controlled temperature of 220 °C. Subsequently, the mixture's temperature was gradually reduced to 80 °C, at which point, 40.4 g of nadic methyl anhydride (MNA) and 0.4 g of the accelerator benzyl dimethylamine were added. The curing process was then executed, maintaining a precise temperature of 120 °C for 20 h. These procedures culminated in the production of a visually transparent sheet of material.

2.2. Gamma Irradiation

The composite samples, consisting of highly cross-linked epoxy resin as the matrix and filled with bisphenol A-based polycarbonate at varying concentrations of 0%, 4%, 8%, 10%, and 15% by weight, were subjected to gamma radiation exposure at absorbed doses

of 0 Gy, 100 Gy, 300 Gy, and 500 Gy. The irradiation experiments were carried out under ambient conditions, utilizing a 60 Co gamma source with an average energy of 1.25 MeV and a dose rate of 4163.511 Gy/hr, at the gamma irradiation facility of the Jordan Atomic Energy Commission.

2.3. Electrical Parameters Calculations

To measure the impedance magnitude (Z) and the phase angle (φ), the Low-Frequency Impedance Analyzer (HP model 4192) was used, while the complex impedance (Z^*) with the real (Z_r) and imaginary (Z_i) components were calculated using the following famous formula:

$$Z^* = Z_r + iZ_i \tag{1}$$

where $Z_r = Zcos\varphi$ and $Z_i = Zsin\varphi$.

The dielectric constant (ε_r) is given by:

$$\varepsilon_r = \frac{Z_i}{2\pi f C_o Z^2} \tag{2}$$

and dielectric loss (ε_i) is given by:

$$\varepsilon_i = \frac{Z_r}{2\pi f C_o Z^2} \tag{3}$$

where C_o is the capacitance of the sample two plates, given by the following formula:

$$C_o = \epsilon_o \frac{A}{d} \tag{4}$$

where A is the disk area, and d is the distance between the two plates of the sample.

The AC electrical conductivity (σ_{AC}) of the sample was calculated via:

$$\sigma_{AC} = 2\pi f \epsilon_o \varepsilon_i \tag{5}$$

where f is the applied frequency and ϵ_o is the permittivity of free space.

The activation energy for any thermally activated transport process is calculated using the Arrhenius equation:

$$\sigma = \sigma_o e^{\left(-\frac{E_a}{k_B T}\right)} \tag{6}$$

where:

σ is the conductivity and σ_o is the pre-exponential factor of conductivity, which measures the units of conductivity;

k_B is the Boltzmann constant;

T is the temperature in Kelvin;

E_a is the activation energy for the migration of free charges.

3. Results and Discussion

This study's Figure 1 presents an analysis of the behavior of Z^* as a function of the frequency ranging from 200 kHz to 1 MHz, both pre- and post gamma irradiation, for our highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples. Figure 1a illustrates the pre-irradiation Z^* values, in the range of 0.907×10^5 to 0.183×10^5 ohms.

Figure 1b illustrates the post-irradiation case, where the samples were subjected to a dose of 100 Gy, with a composition of 85 wt% epoxy and 15 wt% polycarbonate. Notably, the Z^* values following irradiation are lower when compared to their pre-irradiation counterparts. Specifically, they decreased from the initial range of 0.907×10^5–0.183×10^5 ohms to a range of 0.886×10^5–0.180×10^5 ohms, while Figure 1c shows that the Z^* values

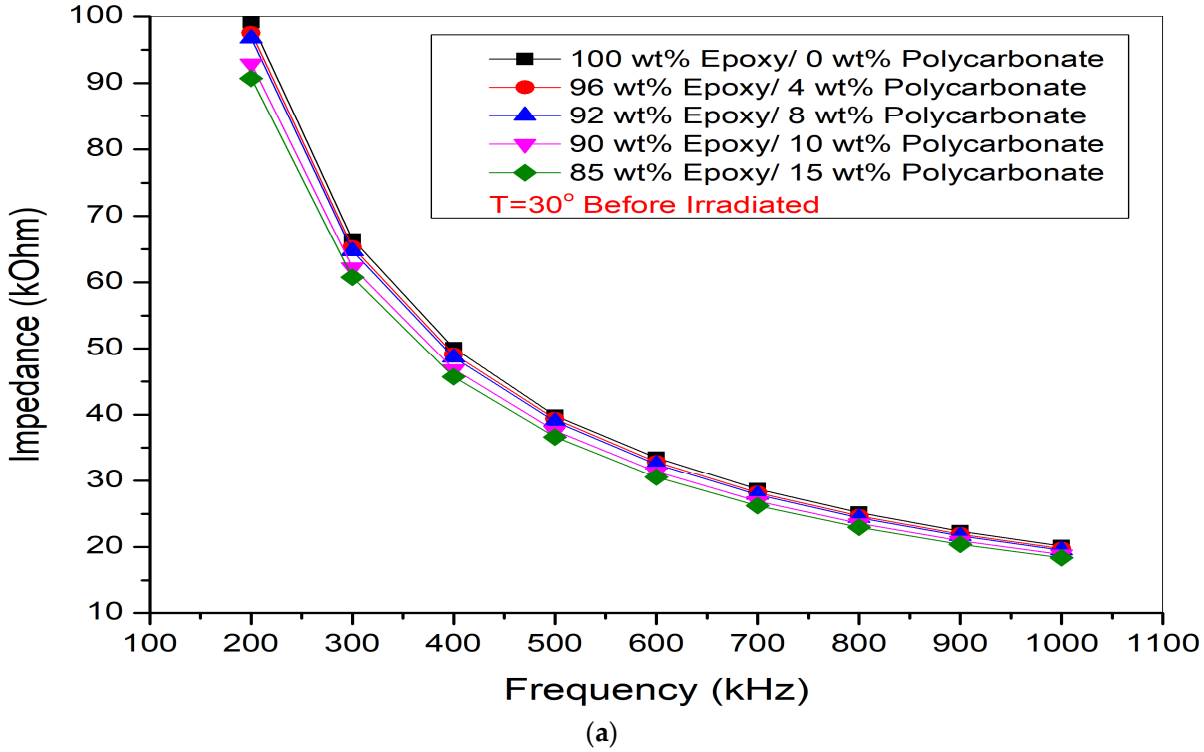
further decreased to 0.819 × 10^5–0.164 × 10^5 ohms after exposure to a dose of 300 Gy. Finally, Figure 1d illustrates the Z^* behavior post irradiation with a more substantial dose of 500 Gy. Here, the Z^* values decreased to 0.781 × 10^5–0.158 × 10^5 ohms, and the results of the Z^* analysis for all samples are shown in Table 1.

Table 1. The values of Z^* with frequencies ranging from 200 kHz to 1 MHz for highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples at T = 30 °C.

Sample	(Pre–Irradiation) × 10^5 ohms	(at 100 Gy) × 10^5 ohms	(at 300 Gy) × 10^5 ohms	(at 500 Gy) × 10^5 ohms
100 wt% Epoxy/0 wt% Polycarbonate	0.991–0.202	0.977–0.199	0.956–0.194	0.905–0.184
96 wt% Epoxy/4 wt% Polycarbonate	0.974–0.198	0.967–0.196	0.928–0.189	0.875–0.178
92 wt% Epoxy/8 wt% Polycarbonate	0.967–0.195	0.910–0.183	0.869–0.176	0.864–0.175
90 wt% Epoxy/10 wt% Polycarbonate	0.929–0.189	0.899–0.182	0.851–0.173	0.834–0.169
85 wt% Epoxy/15 wt% Polycarbonate	0.907–0.183	0.886–0.180	0.819–0.164	0.781–0.158

From the above results, it can be concluded that the consistent decrease in Z^* values post irradiation indicates that the charge carriers within the samples are influenced by radiation-induced scission of the composite structure. This scission process generates additional free charges that become trapped in localized sites within the polymeric composites [24].

The lower Z^* values are likely attributed to the energy released from gamma radiation, which releases more free charges into the system. Additionally, it is plausible that the radiation creates holes within the material, potentially facilitating the movement of these free charges and enhancing the conductivity of the composite samples [8].



(**a**)

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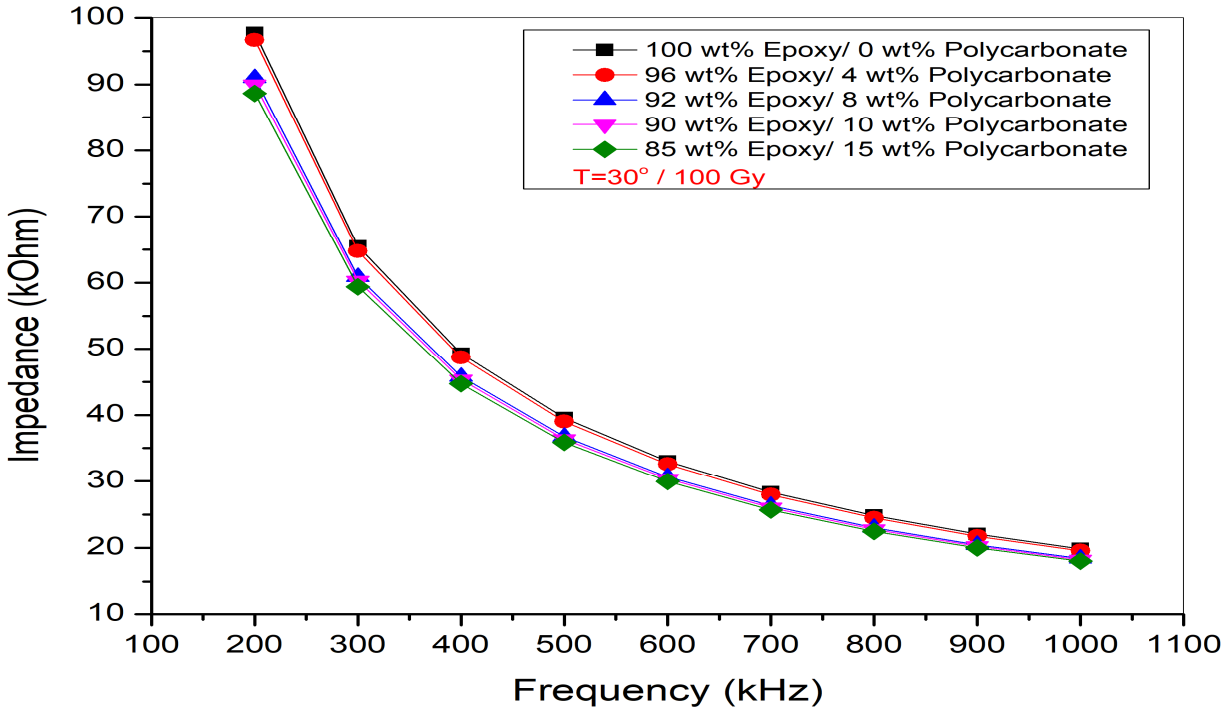

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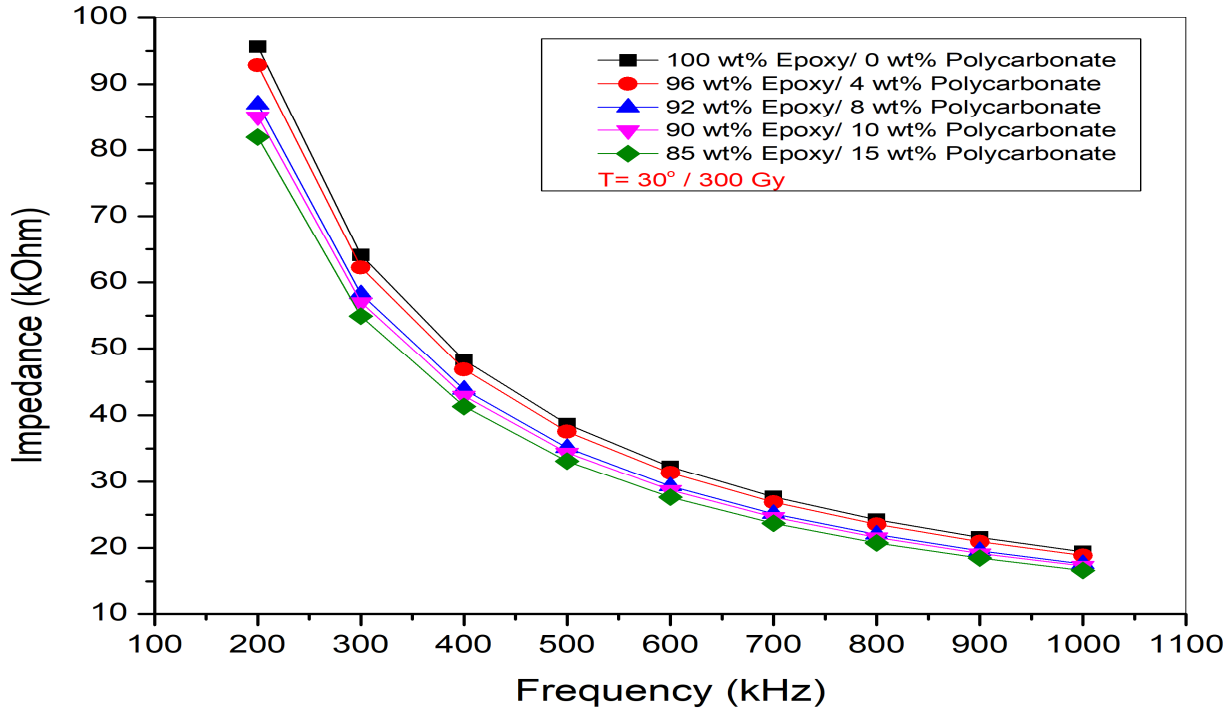

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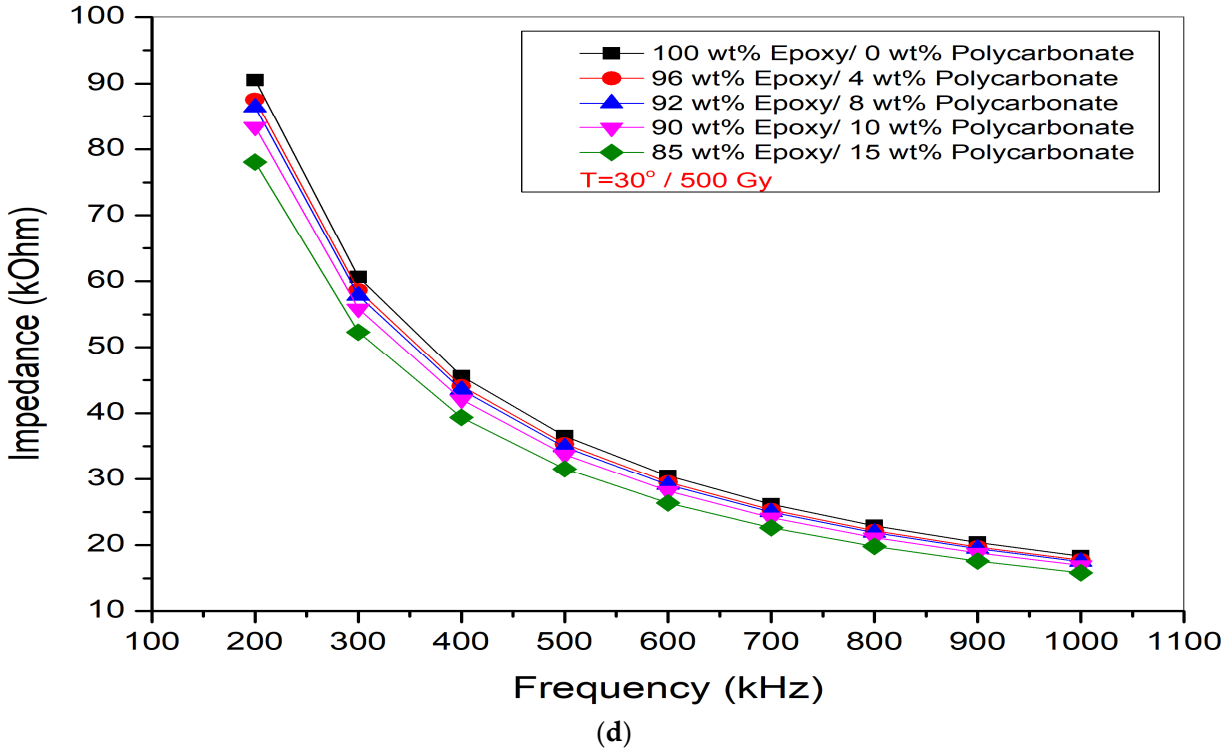

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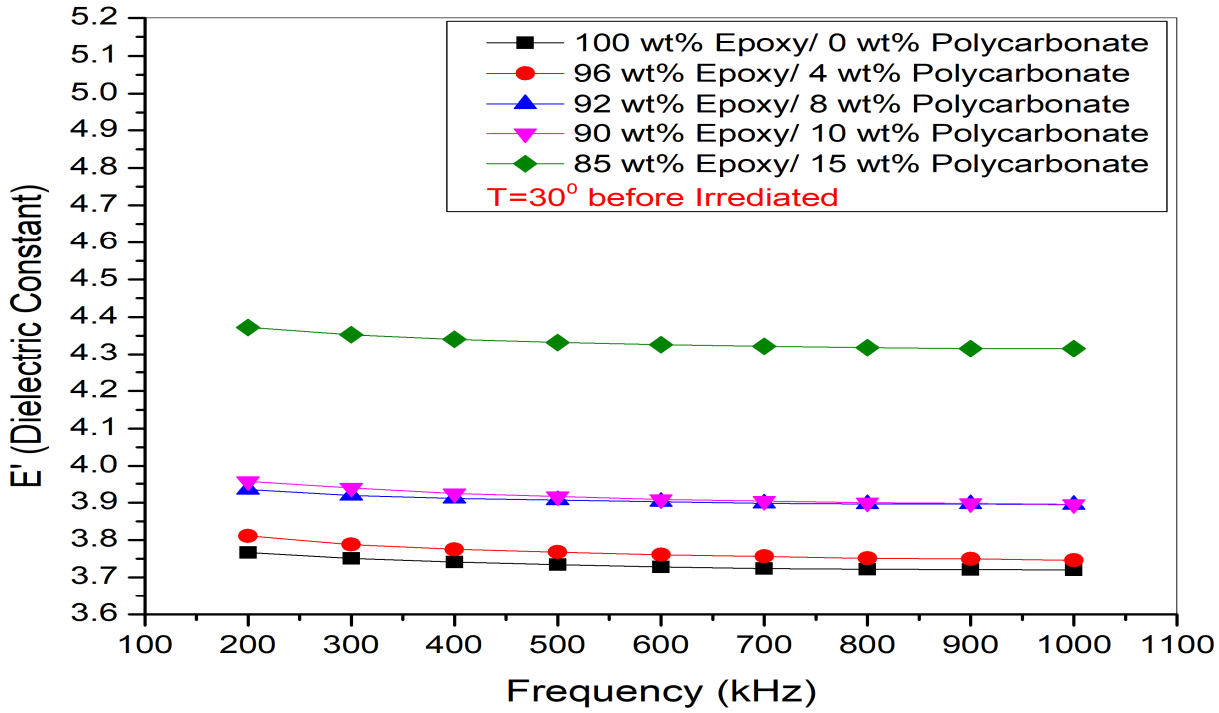
Figure 1. Variations in the Z^* value across different frequencies for highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples at T = 30 °C. (**a**): Pre-irradiation; (**b**): at 100 Gy; (**c**): at 300 Gy; (**d**): at 500 Gy.

In Figure 2, one result of the ε_r behavior is presented as a function of the frequency both pre- and post exposure to gamma irradiation doses of 100 Gy, 300 Gy, and 500 Gy, maintaining a sample composition of 85 wt% epoxy and 15 wt% polycarbonate, within a frequency range of 200 kHz to 1 MHz. The pre-irradiation ε_r values are shown in Figure 2a, and they fall within a range of 4.372 to 4.315; and for the post-irradiation of 100 Gy gamma dose, the ε_r values are shown in Figure 2b. Remarkably, the ε_r values for the irradiated samples are relatively higher compared to their non-irradiated counterparts. Specifically, they increased from an initial range of 4.372–4.315 to a new range of 4.474–4.399. In Figure 2c, at a dose of 300 Gy, the ε_r values show an increase, within the range of 4.841–4.767. Figure 2d extends this analysis to a gamma irradiation dose of 500 Gy. In this case, the ε_r values continued to rise and spanned a range of 5.081–5.001, and the results of the ε_r analysis for all samples are shown in Table 2.

Table 2. The ε_r values with frequencies ranging from 200 kHz to 1 MHz for highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples at T = 30 °C.

Sample	(Pre–Irradiation)	(at 100 Gy)	(at 300 Gy)	(at 500 Gy)
100 wt% Epoxy/0 wt% Polycarbonate	3.767–3.721	3.800–3.752	3.951–3.887	4.174–4.117
96 wt% Epoxy/4 wt% Polycarbonate	3.811–3.746	3.866–3.802	3.957–3.894	4.197–4.140
92 wt% Epoxy/8 wt% Polycarbonate	3.935–3.894	4.087–4.030	4.321–4.250	4.410–4.336
90 wt% Epoxy/10 wt% Polycarbonate	3.958–3.895	4.183–4.127	4.377–4.316	4.412–4.340
85 wt% Epoxy/15 wt% Polycarbonate	4.372–4.315	4.474–4.399	4.841–4.767	5.081–5.001

Therefore, the ε_r value increases with the rising dose of ionizing gamma radiation due to polymer chain scission and the formation of a few numbers of defect sites within the composites' band gaps as the radiation passes through them. These defects trap the charge carriers found within the band gaps of the samples. Furthermore, gamma radiation enhances the samples' capability to store charges.



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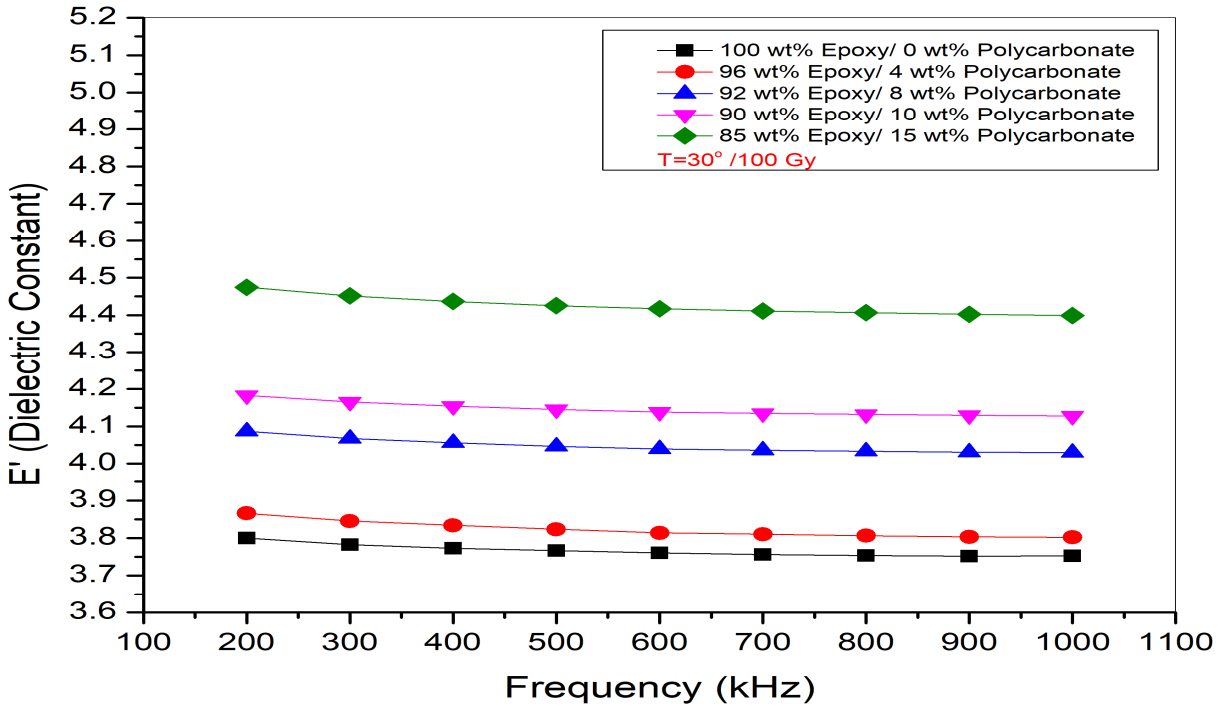

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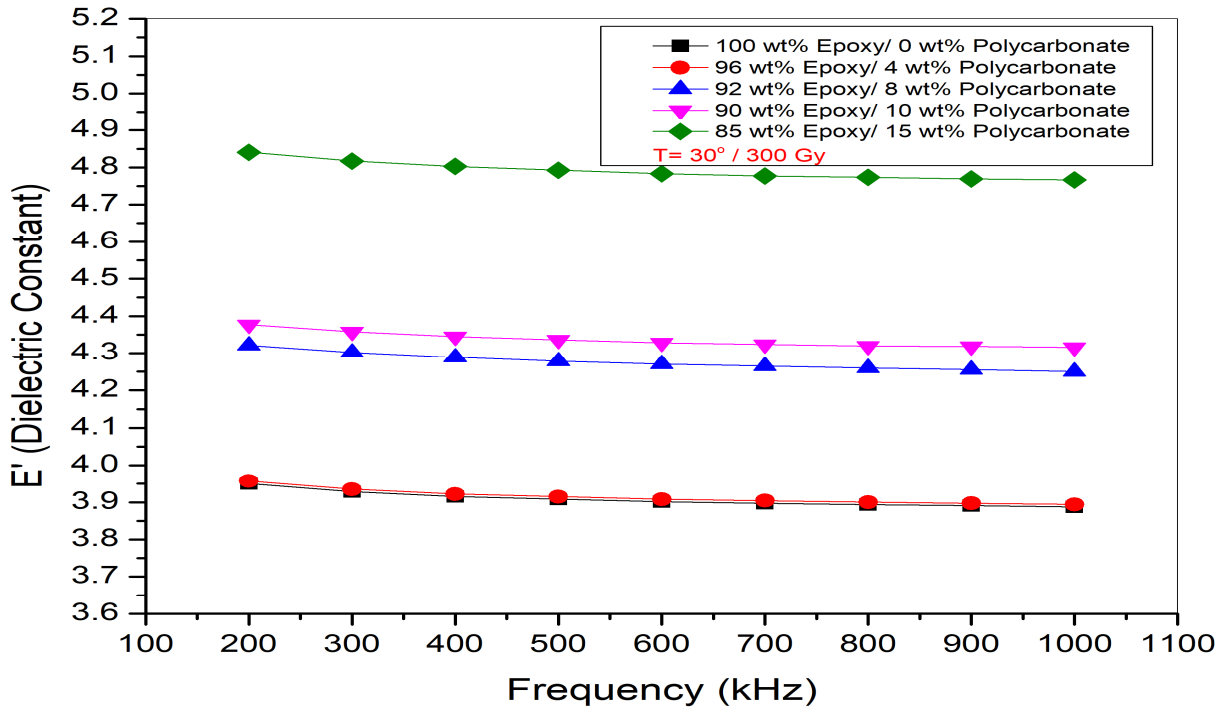

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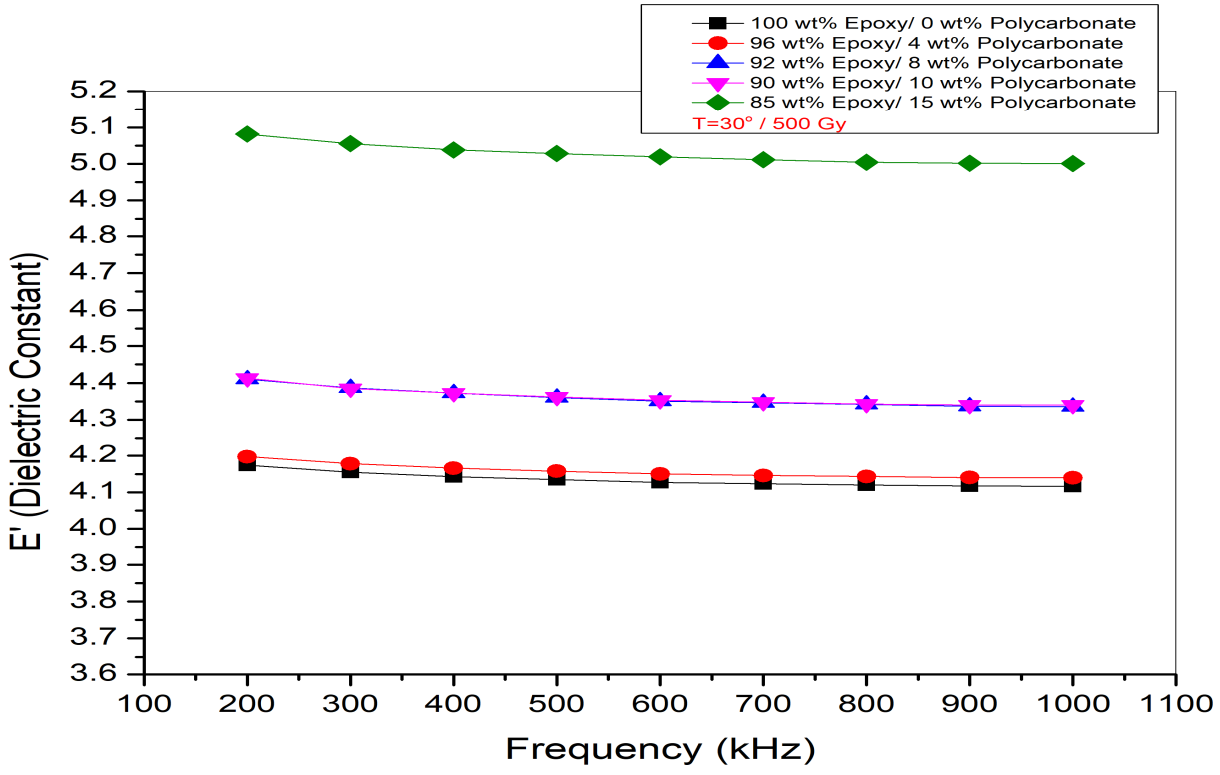

(**d**)

Figure 2. Variations in the ε_r value across different frequencies for highly cross-linked epoxy resin/bisphenol A-based polycarbonate composites at T = 30 °C. (**a**): Pre-irradiation; (**b**): at 100 Gy; (**c**): at 300 Gy; (**d**): at 500 Gy.

It is also predicted that an increase in radiation dose will result in greater charge carrier delocalization, ultimately leading to a higher ε_r. Additionally, the ε_r increases with higher concentrations of polycarbonate because the incorporation of this material into the composite samples results in a greater number of dipoles, which, in turn, raises the ε_r [25,26].

Figure 3 illustrates the variations in ε_i as a function of the frequency, within the range of 200 kHz to 1 MHz, both pre- and post exposure to gamma irradiation at different doses (100, 300, and 500 Gy) for our highly cross-linked epoxy resin/bisphenol A-based samples with an 85 wt% epoxy and 15 wt% polycarbonate. Pre-irradiation, the ε_i values for the samples fell within the range of 0.134 to 0.116, as seen in Figure 3a. Notably, an intriguing trend emerged, revealing that the ε_i values decreced with escalations in the frequency. This is because as the frequency is raised, the generated charges rapidly lose their ability to follow the reverse field, which reduces their electronic oscillations [27]. Post irradiation at a dose of 100 Gy, Figure 3b shows a notable enhancement in the ε_i values when compared to the non-irradiated samples. This enhancement led to a shift in the ε_i range, from 0.134–0.116 to 0.137–0.119. Subsequently, when subjected to a higher irradiation dose of 300 Gy, as seen in Figure 3c, the ε_i values further increased, spanning a range of 0.149 to 0.130 over the same frequency range of 200 kHz to 1 MHz. The most striking effect was observed at the highest irradiation dose of 500 Gy (see Figure 3d), where the ε_i values exhibited a significant increase, extending their range from 0.157 to 0.138, and the results of the ε_i analysis for all samples are shown in Table 3.

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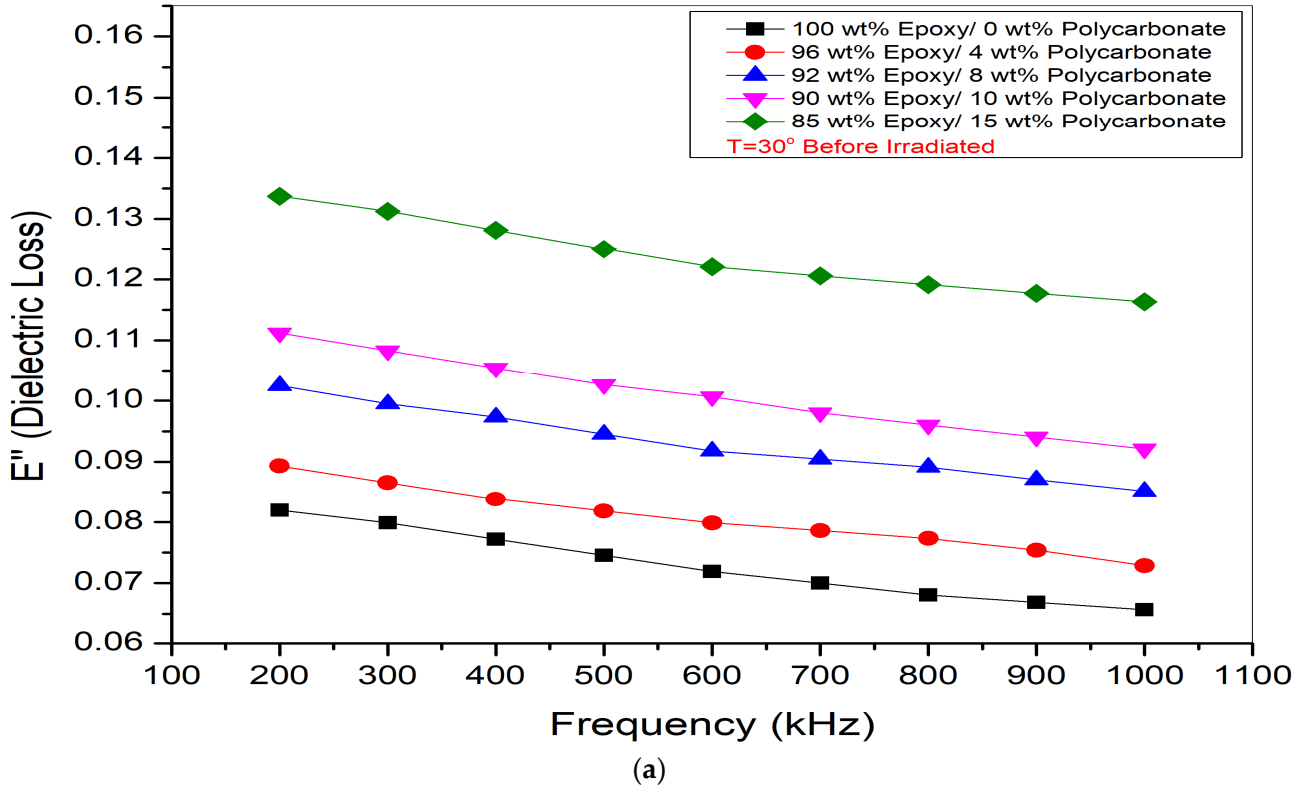

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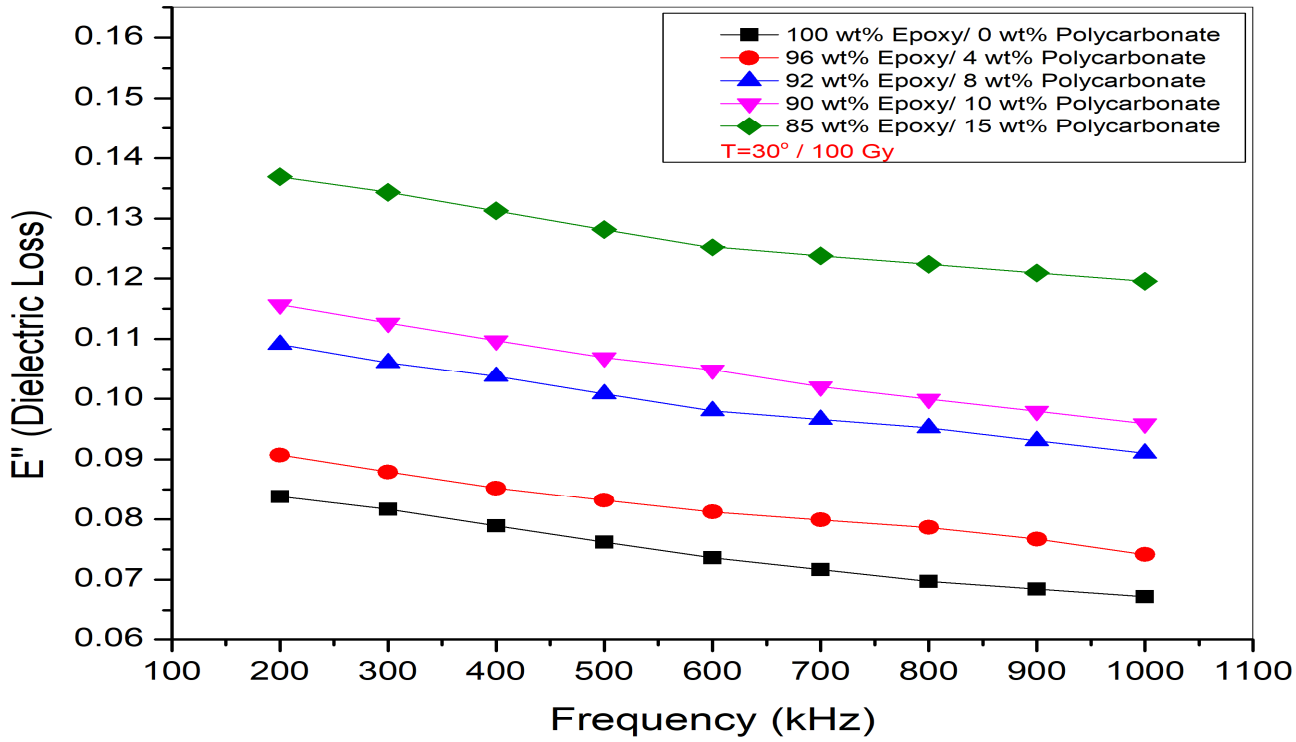

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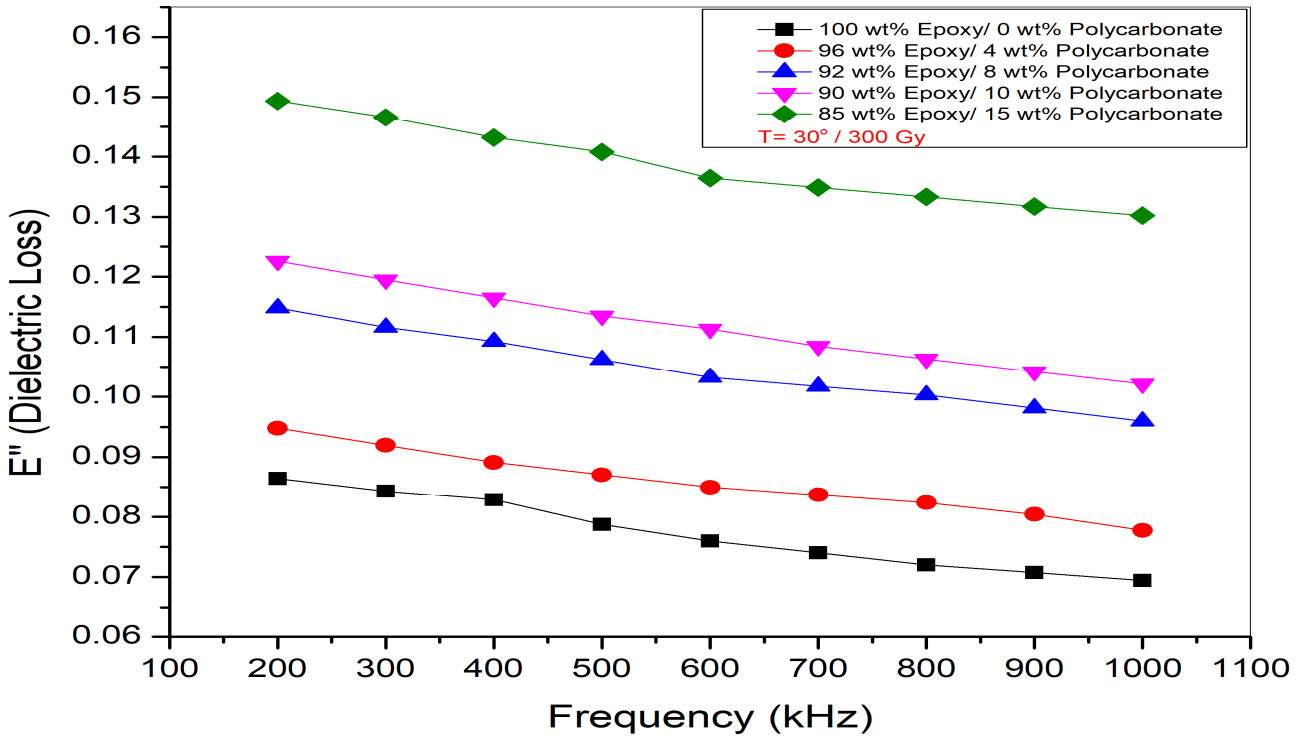

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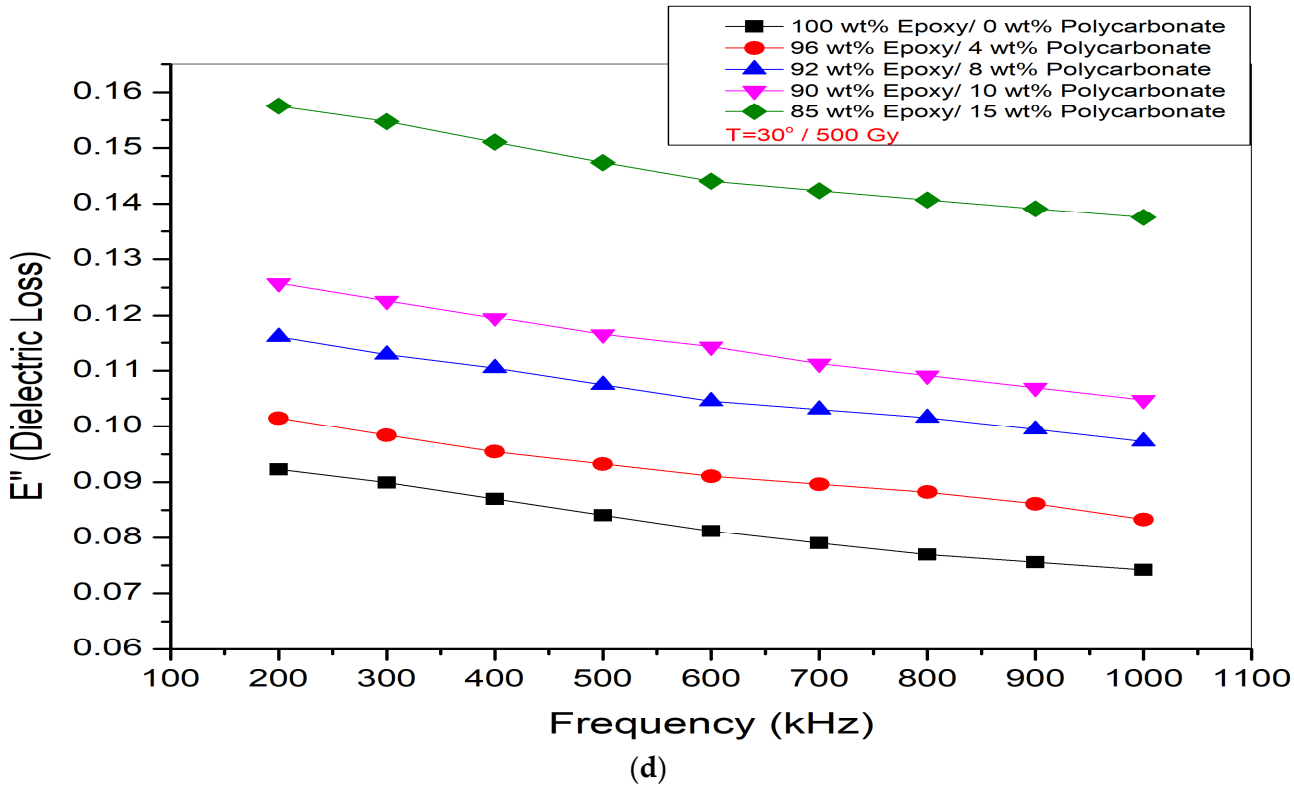
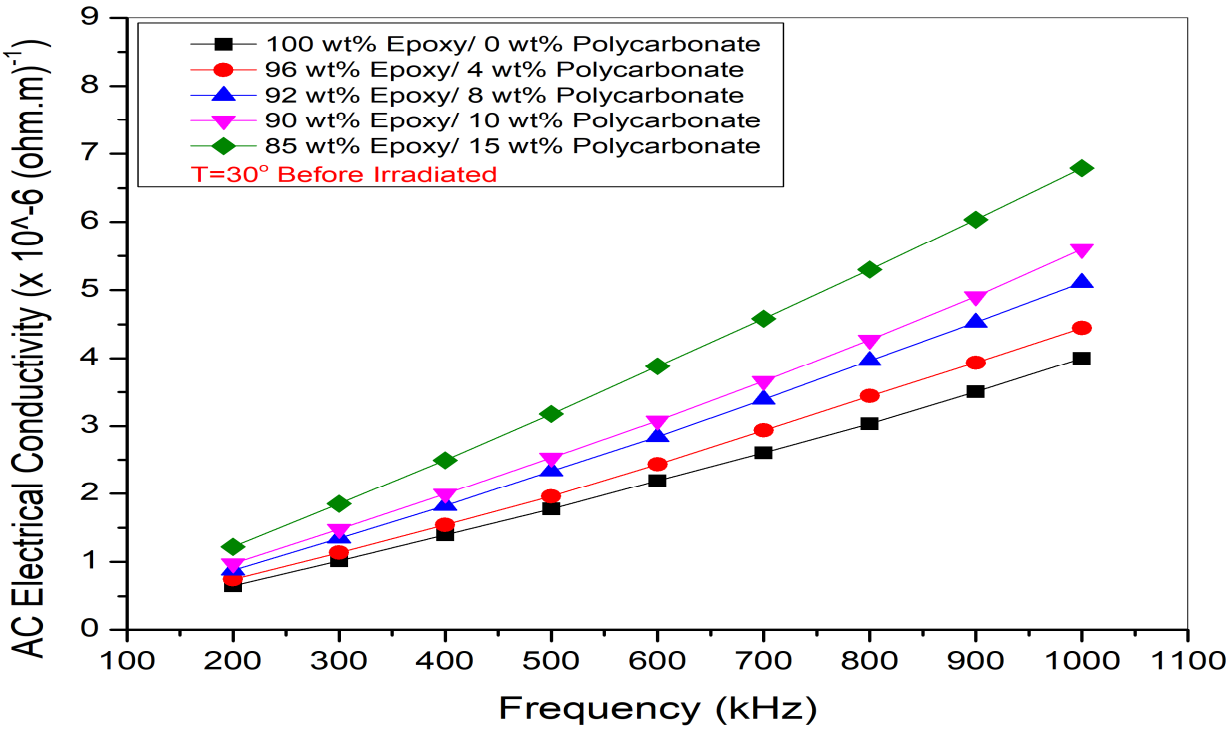


Figure 3. Variations in the ε_i value across different frequencies for highly cross-linked epoxy resin/bisphenol A-based polycarbonate composites at T = 30 °C. (**a**): Pre-irradiation; (**b**): at 100 Gy; (**c**): at 300 Gy; (**d**): at 500 Gy.

Table 3. The ε_i values with frequencies ranging from 200 kHz to 1 MHz for highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples at T = 30 °C.

Sample	(Pre–Irradiation)	(at 100 Gy)	(at 300 Gy)	(at 500 Gy)
100 wt% Epoxy/0 wt% Polycarbonate	0.082–0.066	0.084–0.067	0.086–0.069	0.092–0.074
96 wt% Epoxy/4 wt% Polycarbonate	0.089–0.073	0.091–0.074	0.095–0.078	0.101–0.083
92 wt% Epoxy/8 wt% Polycarbonate	0.102–0.085	0.109–0.091	0.115–0.096	0.116–0.097
90 wt% Epoxy/10 wt% Polycarbonate	0.111–0.092	0.116–0.096	0.123–0.102	0.126–0.105
85 wt% Epoxy/15 wt% Polycarbonate	0.134–0.116	0.137–0.119	0.149–0.130	0.157–0.138

Figure 4 depicts the variations in σ_{ac} as a function of the frequency, across a frequency range of 200 kHz to 1 MHz, both pre- and post gamma irradiation for our highly cross-linked epoxy resin/bisphenol A-based samples with an 85 wt% of epoxy and 15 wt% of polycarbonate. Before gamma irradiation, Figure 4a reveals that the σ_{ac} values for the samples were within a range of 1.223×10^{-6}–6.789×10^{-6} $(\text{ohms}\cdot\text{m})^{-1}$. Upon irradiation at a dose of 100 Gy (see Figure 4b), a noticeable increase in the σ_{ac} values was observed in comparison to the pre-irradiation samples. The conductivity range shifted from 1.223×10^{-6}–6.789×10^{-6} $(\text{ohms}\cdot\text{m})^{-1}$ to 1.260×10^{-6}–6.964×10^{-6} $(\text{ohms}\cdot\text{m})^{-1}$ over the same frequency range. Subsequently, at an irradiation dose of 300 Gy, Figure 4c showcases a further increase in the σ_{ac} values, which spanned a range of 1.373×10^{-6}–7.592×10^{-6} $(\text{ohms}\cdot\text{m})^{-1}$. The most pronounced effect was observed at the highest irradiation dose of 500 Gy, as seen in Figure 4d, where the σ_{ac} values exhibited a significant increase, expanding their range from 1.451×10^{-6} to 8.014×10^{-6} $(\text{ohms}\cdot\text{m})^{-1}$; the results of the ε_i analysis for all samples are shown in Table 4.



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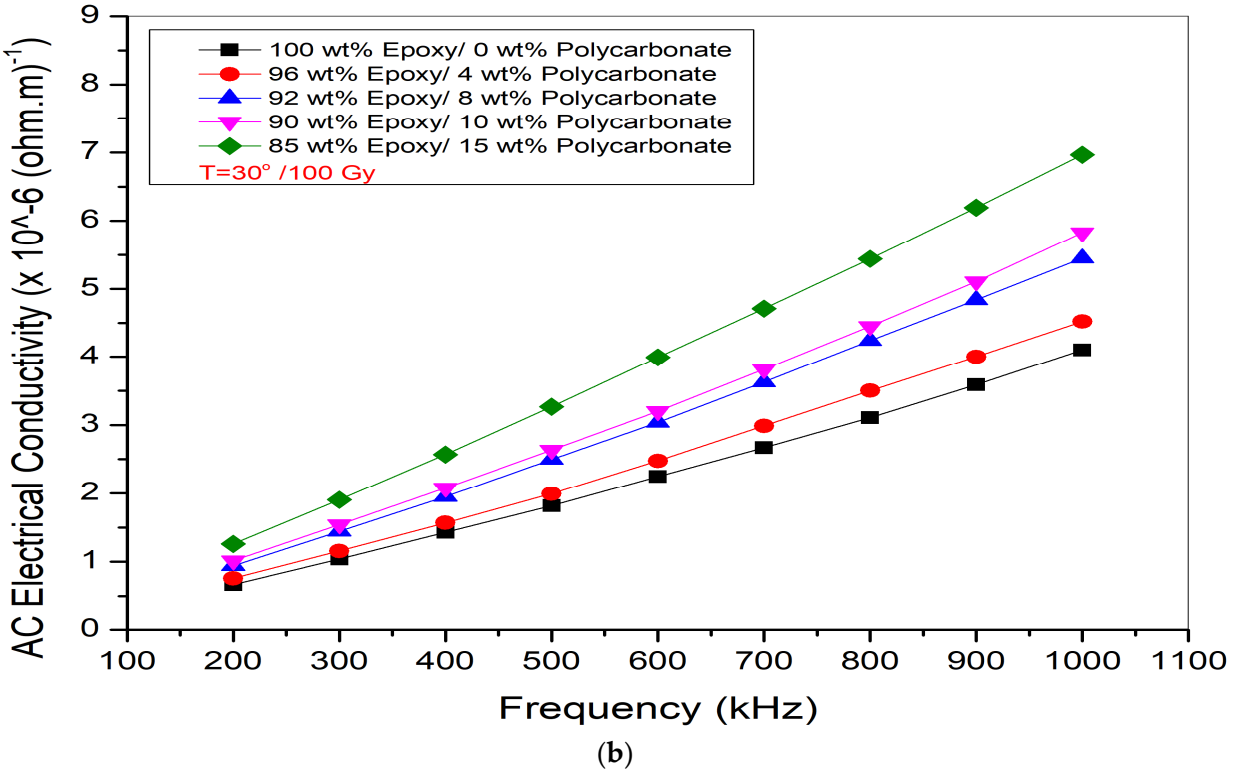

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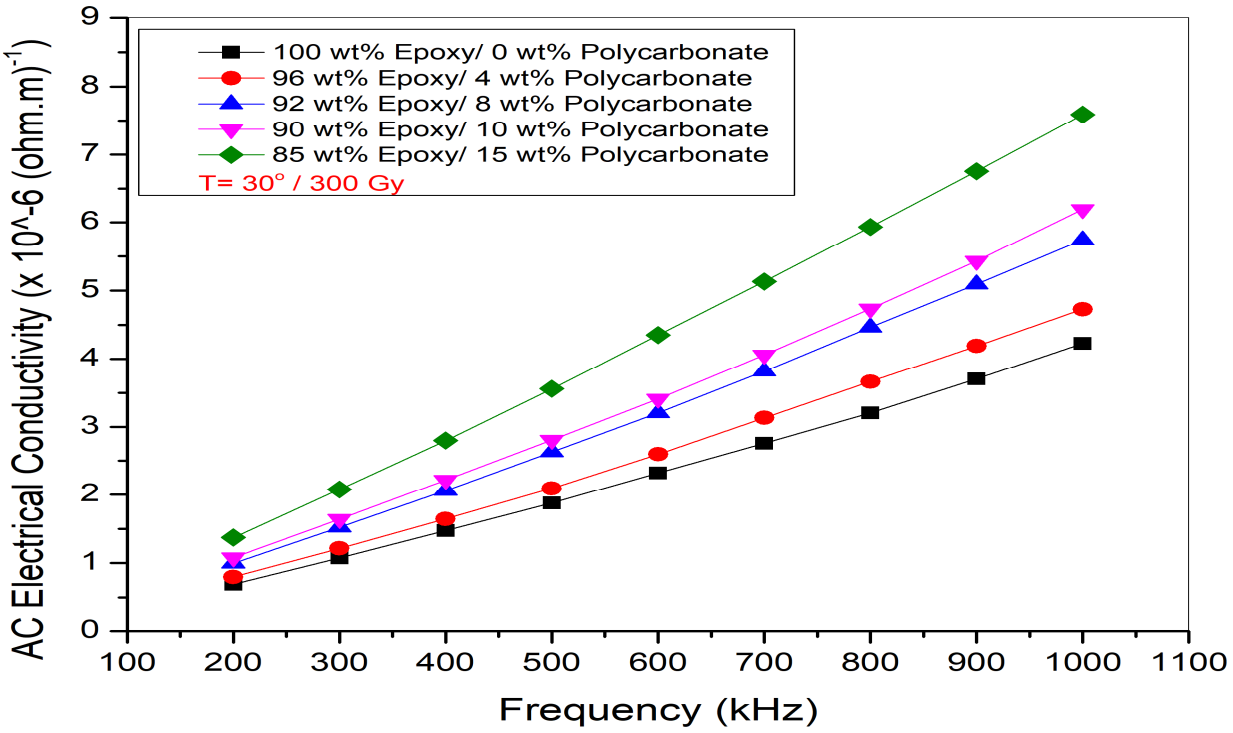

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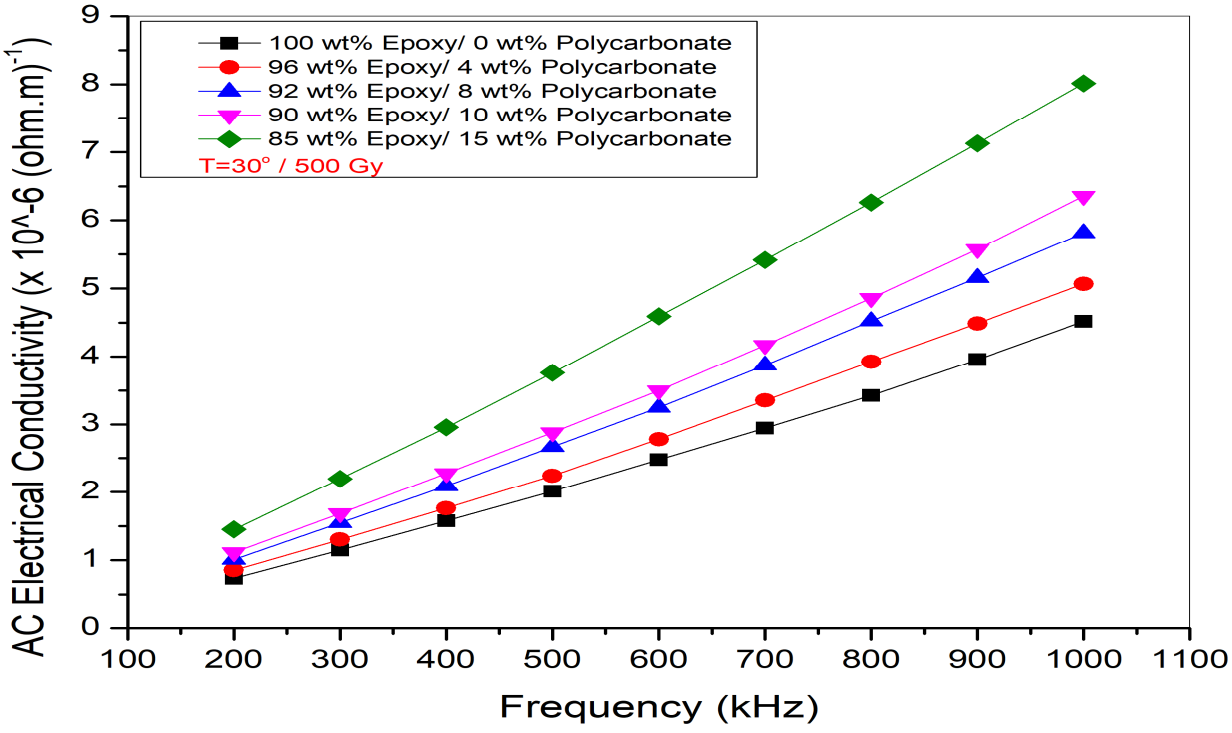


(**d**)

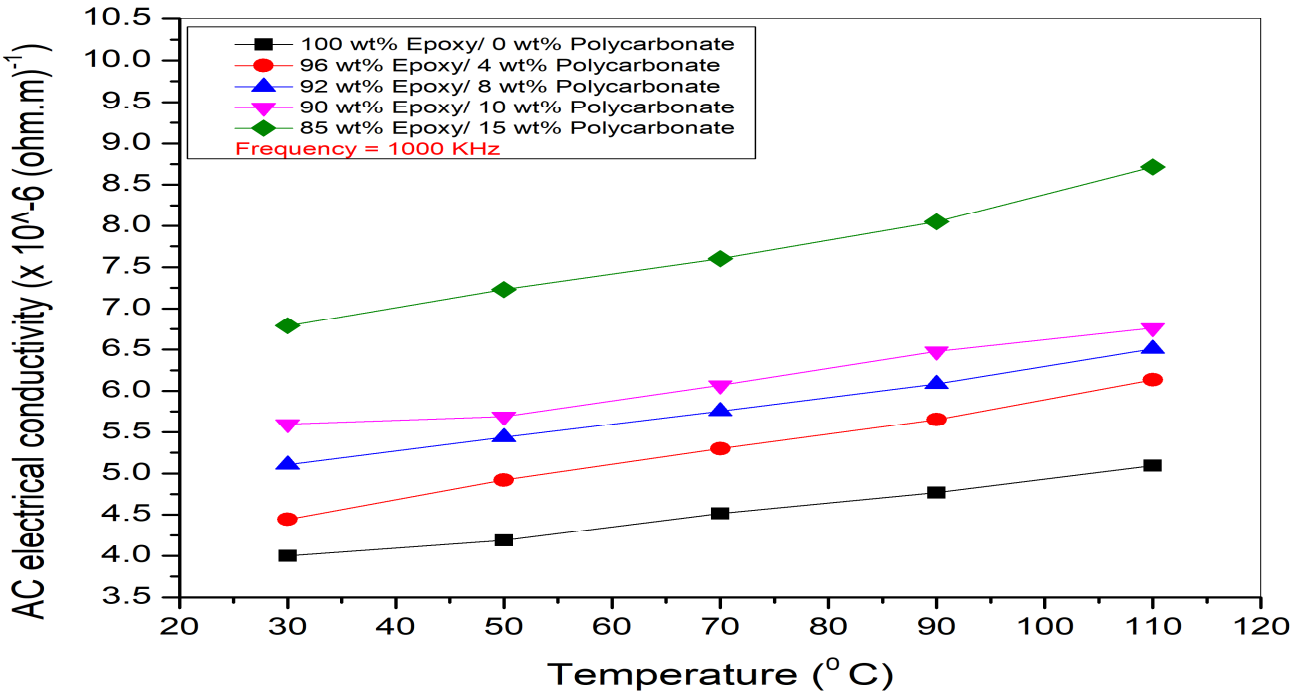
Figure 4. Variations in the σ_{ac} value across different frequencies for highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples at T = 30 °C. (**a**): Pre-irradiation; (**b**): at 100 Gy; (**c**): at 300 Gy; (**d**): at 500 Gy.

Ions and free radicals are created and partly trapped in the bulk of the material after the samples were exposed to gamma radiation. As a result, the conductivity of the irradiated samples was greater than that of the non-irradiatedsamples [26].

Table 4. The σ_{ac} values with frequencies ranging from 200 kHz to 1 MHz for highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples at T = 30 °C.

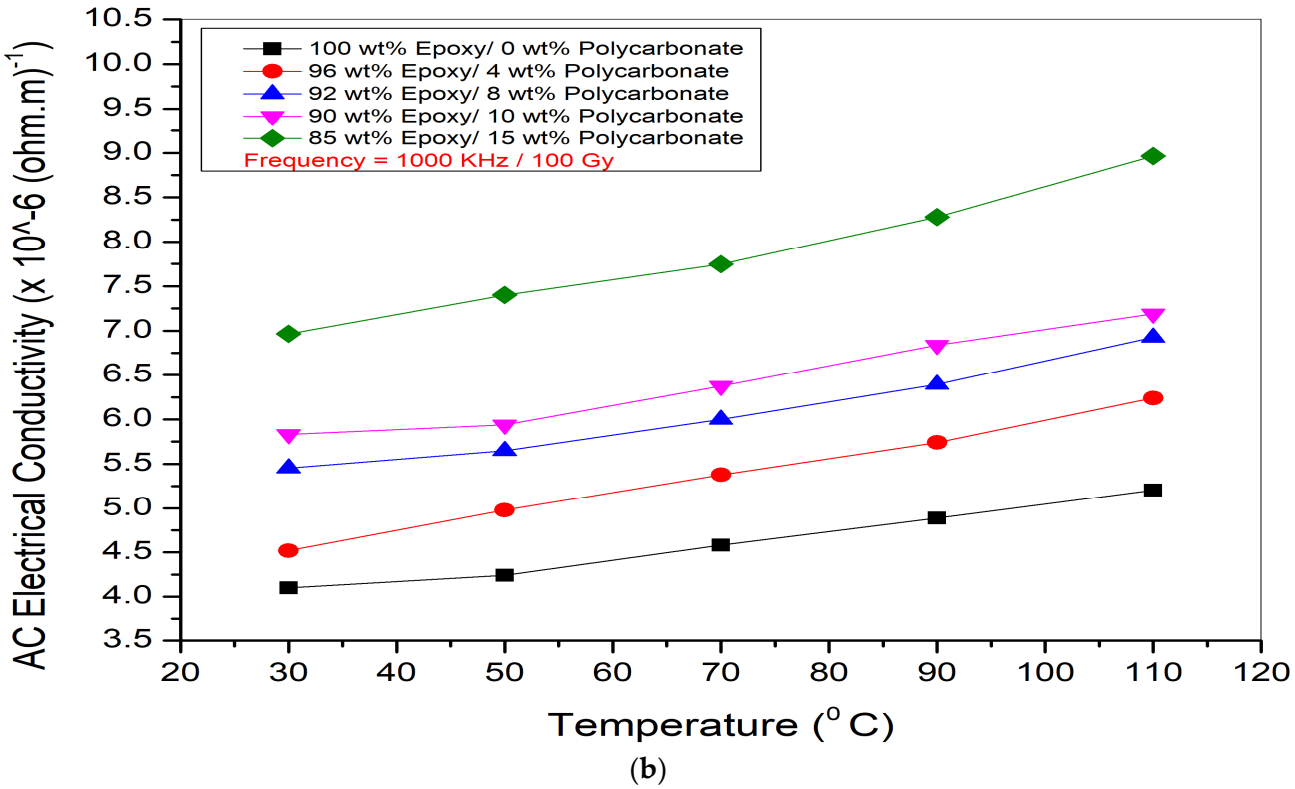
Sample	(Pre–Irradiation) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 100 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 300 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 500 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$
100 wt% Epoxy/0 wt% Polycarbonate	0.651–4.00	0.668–4.100	0.691–4.228	0.738–4.517
96 wt% Epoxy/4 wt% Polycarbonate	0.746–4.444	0.760–4.519	0.799–4.727	0.856–5.066
92 wt% Epoxy/8 wt% Polycarbonate	0.878–5.105	0.942–5.452	0.995–5.742	1.010–5.817
90 wt% Epoxy/10 wt% Polycarbonate	0.976–5.598	1.016–5.832	1.082–6.192	1.114–6.358
85 wt% Epoxy/15 wt% Polycarbonate	1.223–6.789	1.260–6.964	1.373–7.592	1.451–8.014

Figure 5 provides insights into the behavior of the σ_{ac} for the tested samples as a function of the temperature, at temperatures ranging from 30 °C to 110 °C and at a fixed frequency of 1 MHz, both pre- and post gamma irradiation. In Figure 5a, the results depict the σ_{ac} values pre-gamma irradiation, revealing a direct correlation between the temperature and σ_{ac}. Additionally, it is noteworthy that increases in the weight percentages of the polycarbonate particles, ranging between 0%, 4%, 8%, 10%, and 15%, led to an increase in the σ_{ac} values. Figure 5b showcases the impact of the 100 Gy gamma irradiation dose on the σ_{ac} values. Here, a notable increase in σ_{ac} can be observed compared to the pre-irradiation samples. The σ_{ac} values escalated from a range of 6.789 $\times 10^{-6}$ to 8.717 $\times 10^{-6}$ (ohms·m)$^{-1}$ to a range of 6.964 $\times 10^{-6}$ to 8.962 $\times 10^{-6}$ (ohms·m)$^{-1}$. Continuing with the irradiation dose of 300 Gy, as seen in Figure 5c, the σ_{ac} further increased from 7.592 $\times 10^{-6}$ to 9.733 $\times 10^{-6}$ (ohms·m)$^{-1}$, showcasing the pronounced impact of gamma irradiation on σ_{ac}. At the highest irradiation dose of 500 Gy, depicted in Figure 5d, the σ_{ac} values experienced a substantial boost, extending their range from 8.014 $\times 10^{-6}$ to 10.080 $\times 10^{-6}$ (ohms·m)$^{-1}$ within the same temperature range. The results presenting the σ_{ac} as a function of the temperature, within a range of 30 to 110 °C, for all samples are shown in Table 5.

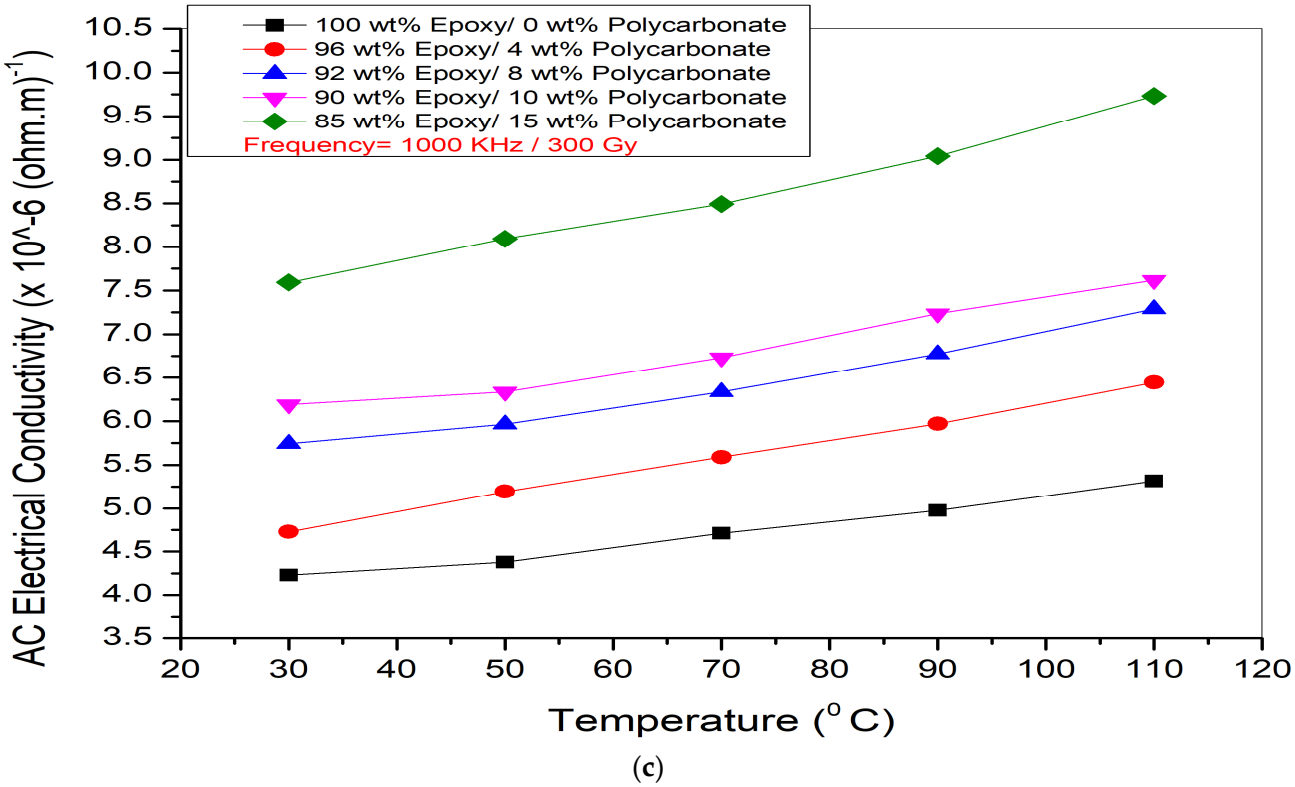


(**a**)

Figure 5. *Cont.*



(b)



(c)

Figure 5. *Cont.*

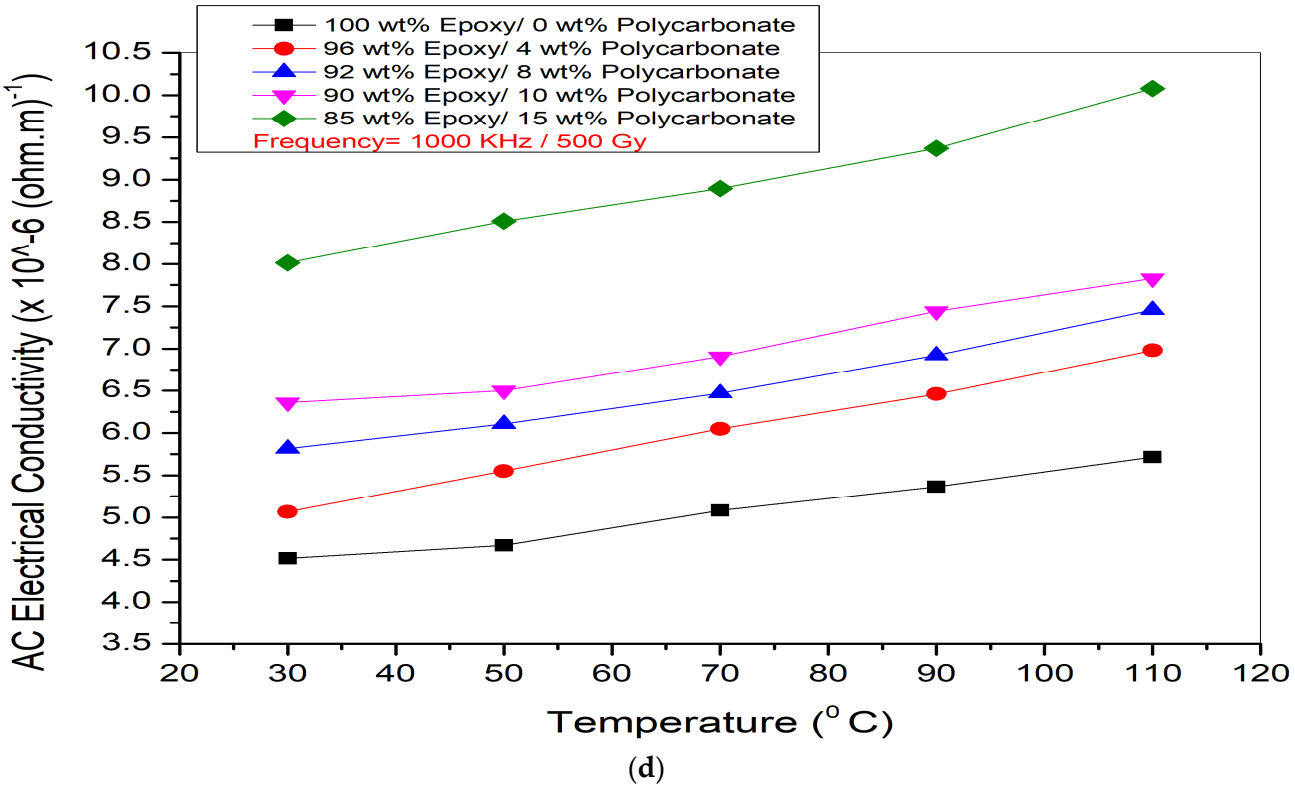


Figure 5. Variations in the AC electrical conductivity across different temperatures for highly cross-linked epoxy resin/bisphenol A-based polycarbonate composites at a frequency of 1 MHz. (**a**): Pre-irradiation; (**b**): at 100 Gy; (**c**): at 300 Gy; (**d**): at 500 Gy.

Table 5. The σ_{ac} values with temperatures ranging from 30 °C to 110 °C for highly cross-linked epoxy resin/bisphenol A-based polycarbonate samples at a frequency of 1 MHz.

Sample	(Pre–Irradiation) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 100 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 300 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 500 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$
100 wt% Epoxy/0 wt% Polycarbonate	4.002–5.095	4.098–5.206	4.228–5.317	4.517–5.717
96 wt% Epoxy/4 wt% Polycarbonate	4.444–6.133	4.519–6.239	4.727–6.445	5.066–6.981
92 wt% Epoxy/8 wt% Polycarbonate	5.105–6.507	5.452–6.926	5.742–7.289	5.817–7.456
90 wt% Epoxy/10 wt% Polycarbonate	5.598–6.760	5.832–7.187	6.192–7.617	6.358–7.830
85 wt% Epoxy/15 wt% Polycarbonate	6.789–8.717	6.964–8.962	7.592–9.733	8.014–10.080

Gamma radiation induces chain scission within the samples, resulting in the emergence of defects, free radicals, and increased electron densities throughout the composite material. Consequently, the irradiated samples exhibit a higher σ_{ac} compared to their non-irradiated counterparts. It is clear that the degradation of polymer chains within the samples plays a pivotal role in the observed increase in σ_{ac} values as the irradiation dose escalates [24,26].

Figure 6 provides the behavior of the σ_{ac} for the tested samples as a function of their filler concentration at a fixed frequency of 1 MHz and a fixed temperature of 30°, both pre- and post gamma irradiation. In Figure 6, it is noteworthy that increases in the weight percentages of the polycarbonate particles ranging between 0%, 4%, 8%, 10%, and 15% led to an increase in σ_{ac} values, and it can be observed that the AC electrical conductivity (σ_{ac}) displayed a notable rise following irradiation with different gamma doses of 100, 300, and 500 Gy. The results presenting the σ_{ac} as a function of the filler concentration, at a fixed frequency of 1 MHz and fixed temperature of 30°, for all samples are shown in Table 6.

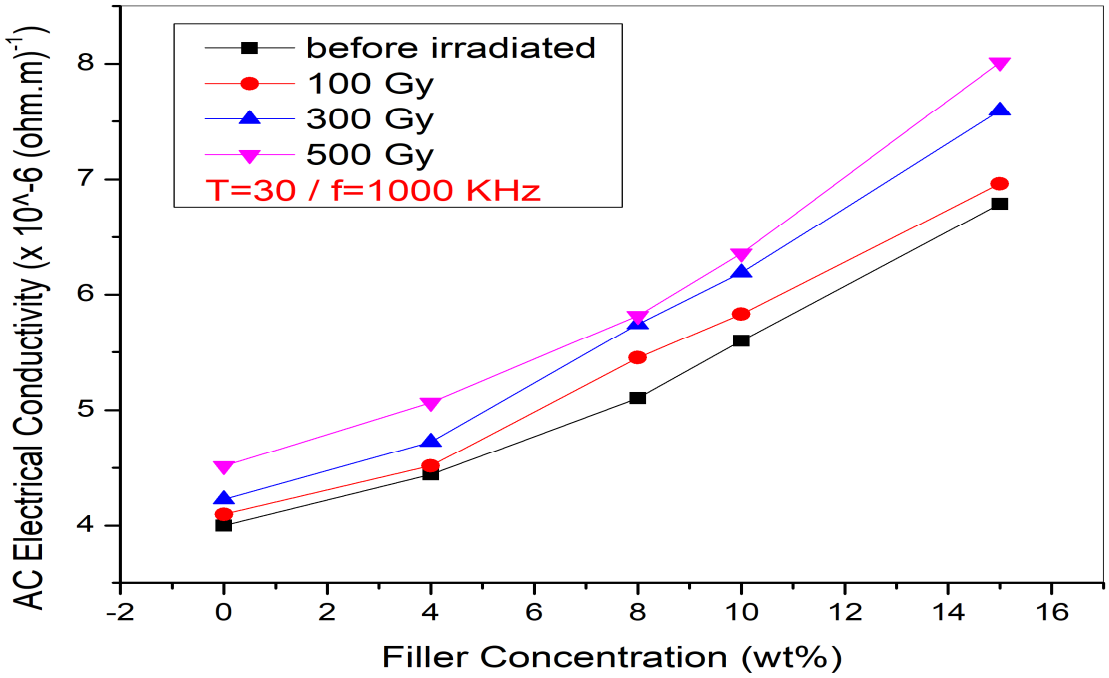


Figure 6. Variations in the AC electrical conductivity across different filler concentrations (0, 4, 8, 10, and 15 wt%) of bisphenol A-based polycarbonate samples at a frequency of 1 MHz and temperature of 30°, at different gamma doses of 0, 100, 300, and 500 Gy.

Table 6. The σ_{ac} values across different filler concentrations (0, 4, 8, 10 and 15 wt%) of bisphenol A-based polycarbonate, at a frequency of 1 MHz and temperature of 30°.

Sample	(Pre–Irradiation) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 100 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 300 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$	(at 500 Gy) $\times 10^{-6}$ (ohms·m)$^{-1}$
100 wt% Epoxy/0 wt% Polycarbonate	4.002	4.098	4.228	4.517
96 wt% Epoxy/4 wt% Polycarbonate	4.444	4.519	4.727	5.066
92 wt% Epoxy/8 wt% Polycarbonate	5.105	5.452	5.742	5.817
90 wt% Epoxy/10 wt% Polycarbonate	5.598	5.832	6.192	6.358
85 wt% Epoxy/15 wt% Polycarbonate	6.789	6.964	7.592	8.014

The calculated E_a values are presented in Table 7. It is noteworthy that as the dose of gamma radiation increases, the energy gap within the material decreases. This phenomenon arises because gamma radiation exerts a pronounced influence on the arrangement of the molecules within the samples, disrupting their structure and leading to the formation of imperfections within the material's molecular framework. These changes serve as a clear indication that the electrical properties of the material are undergoing significant alterations due to structural modifications induced by radiation [28].

Table 7. The E_a values of the σ_{ac} (with a frequency of 1 MHz) for all tested samples pre- and post gamma irradiation.

Sample	Pre-Irradiation	at 100 Gy	at 300 Gy	at 500 Gy
100 wt% Epoxy/0 wt% Polycarbonate	30.5×10^{-3}	30.1×10^{-3}	29.4×10^{-3}	28.5×10^{-3}
96 wt% Epoxy/4 wt% Polycarbonate	30.0×10^{-3}	29.4×10^{-3}	28.7×10^{-3}	27.7×10^{-3}
92 wt% Epoxy/8 wt% Polycarbonate	29.3×10^{-3}	28.6×10^{-3}	27.8×10^{-3}	26.8×10^{-3}
90 wt% Epoxy/10 wt% Polycarbonate	28.7×10^{-3}	28.0×10^{-3}	27.1×10^{-3}	25.9×10^{-3}
85 wt% Epoxy/15 wt% Polycarbonate	27.9×10^{-3}	27.1×10^{-3}	26.0×10^{-3}	24.8×10^{-3}

4. Conclusions

This study investigated the electrical properties of highly cross-linked epoxy resin and bisphenol A-based polycarbonate composite materials before and after exposure to gamma radiation. Our findings reveal a significant influence of gamma radiation on the electrical behavior of these composite materials. Post irradiation, there was a consistent decrease in the complex impedance values (Z^*), suggesting that radiation-induced scission of the composite structure led to the release of additional free charges, enhancing conductivity. The dielectric constant (ε_r) and dielectric loss (ε_i) increased with higher doses of radiation, as well as with higher concentrations of polycarbonate in the samples, indicating the formation of defect sites and the trapping of charge carriers. The AC electrical conductivity (σ_{ac}) exhibited a pronounced increase post irradiation, which was more prominent with higher doses of radiation. Temperature also played a crucial role in influencing the electrical conductivity, with higher temperatures resulting in higher σ_{ac} values. Moreover, the activation energy (E_a) decreased with increasing doses of gamma radiation, reflecting structural modifications within the material induced by the radiation. These findings underscore the profound impact of gamma radiation on the electrical properties of composite materials. The creation of defects, free radicals, and increased electron densities within these materials contribute to the observed changes in their electrical behavior. These findings hold immense significance for applications across various domains, including the science of materials, radiation technology, and advanced composite material design. Moreover, they open avenues for further investigations into tailoring the electrical properties of materials via controlled irradiation, presenting promising opportunities for innovation and technological advancement.

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