



Comparative study of Microwave Absorption in Trilayered Hybrid Nanocomposites containing MWCNTs with different aspect ratios

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Abstract

Research in materials science and telecommunications has intensified owing to the increasing demand for lightweight, broadband, and high-performance electromagnetic (EM) absorbers. The efficiency of these absorbers depends significantly on the microstructural features of lossy filler materials. This study examined the influence of the aspect ratio of multi-walled carbon nanotubes (MWCNTs) on the absorption characteristics of trilayered microwave absorbers. Composites comprising E-glass, epoxy, MWCNTs, and nickel zinc ferrite (NZF) were fabricated using MWCNTs with two different aspect ratios of 115 (low) and 315 (high). Experimental measurements and analytical calculations using transmission line theory were used to evaluate the dielectric and magnetic losses and microwave absorption of the prepared composites. The MWCNTs with a lower aspect ratio in the absorber exhibited a bandwidth of 1.8 GHz with a -10 dB reflection loss (RL) at a thickness of 3 mm. For the same thickness, high-aspect-ratio composites achieved an RL of -10 dB across a 3.6 GHz bandwidth. This denotes a significant enhancement in microwave absorption compared with composites with lower aspect ratios in the X-band (8.2–12.4 GHz). These results demonstrate that the use of high-aspect-ratio MWCNTs improves wave interaction, offering an effective method for designing lightweight, broadband absorbers that are ideal for applications in defense, aerospace, and advanced electronic systems.

Keywords: Electromagnetic interference, Multi-layered radar-absorbing material, Nickel zinc ferrite, Nanofillers, Reflection loss

1. Introduction

Microwave absorption plays a pivotal role in numerous modern applications and significantly influences both the industrial and consumer technology sectors. In wireless communication systems, it is critically important to mitigate electromagnetic interference and strengthen the signal clarity in devices such as smartphones and Wi-Fi routers [1–3]. Among the various material systems, nanomaterials have emerged as highly effective microwave absorbers owing to their unique nanoscale structural characteristics. In particular, nanoparticles possess a high surface-to-volume ratio, which means that a large fraction of atoms reside on or near their surface [4]. This feature increases the surface energy and reactivity, thereby enhancing the interactions with electromagnetic waves, particularly in the microwave frequency range. Furthermore, nanoscale dimensions facilitate tunable material properties that are not achievable in bulk materials, including tailored electrical conductivity, magnetic permeability, and dielectric permittivity of the material. Owing to these merits, polymer-based composites containing nanofillers are widely used in microwave absorption and electromagnetic shielding applications [5,6]. Compared with metal- or ceramic-based composites, they offer several benefits, such as high specific strength,

lightweight nature, cost-effectiveness, corrosion resistance, excellent damping behavior, flexibility, and ease of processing. In addition, fiber-reinforced polymer composites provide a balanced combination of structural integrity and microwave absorption capability, making them suitable for a wide range of industrial applications [7]. Moreover, nanocomposites can be designed to exhibit multiple loss mechanisms simultaneously, including dielectric loss, magnetic loss, and interfacial polarization, which collectively enhance their microwave attenuation performance. By precisely tailoring these properties at the nanoscale, lightweight, thin, and highly efficient microwave-absorbing materials can be developed.

Multi-walled carbon nanotubes (MWCNTs) have been extensively explored as microwave absorbing materials because of their high electrical conductivity, large specific surface area, and excellent dielectric loss characteristics [8]. The electromagnetic performance of MWCNTs based composites is strongly influenced by their geometrical features, particularly the aspect ratio, which controls the conductive network formation and percolation threshold. Recent studies on MWCNTs with MoS_2 have confirmed that, high-aspect-ratio MWCNTs enable the development of interconnected conductive networks at lower filler loadings, resulting in enhanced interfacial polarization and improved dielectric loss behavior [9]. In a study by Silva et al., long carbon nanotubes exhibited higher electrical conductivity than short carbon nanotubes [10]. Jou et al. investigated the influence of the MWCNT aspect ratio on electromagnetic (EM) wave attenuation using two distinct aspect ratios [11]. Although previous studies have reported the influence of the aspect ratio of MWCNTs on electrical conductivity and electromagnetic interference shielding performance, its role in governing microwave absorption behavior remains unclear.

In this context, multi-layered microwave absorbing structures have drawn significant attention because of their ability to enhance the absorption performance over a broad frequency range through gradual attenuation and energy dissipation across layers [12–14]. In such systems, the combination of dielectric materials such as MWCNTs, with magnetic fillers enables improved electromagnetic absorption by exploiting both dielectric and magnetic loss mechanisms [15,16]. Recent studies on hybrid nanocomposites and layered architectures have demonstrated enhanced broadband absorption performance [7]. However, investigations into the influence of the aspect ratio of MWCNTs in multi-layered hybrid systems remain limited, providing the motivation for the present study.

Despite the reported advantages of MWCNTs based composites and multi-layered absorber designs, a clear understanding of how the nanotube aspect ratio influences the microwave absorption behavior in hybrid multi-layer systems is still lacking. In particular, the combined effect of the aspect ratio, filler loading, and layer configuration on the attenuation characteristics and bandwidth enhancement has not been thoroughly investigated. Addressing this issue is essential for developing efficient and lightweight radar-absorbing materials (RAM) with improved broadband performance. In this regard, the present study focuses on trilayered hybrid nanocomposites incorporating MWCNTs with different aspect ratios to assess their influence on microwave absorption behavior.

2. Materials and methods

The nanocomposites investigated in this study were prepared as shown in Figure 1 using a polymer resin (Epofine) and fine hard 5200 hardener (Hind Resins and Chemicals), with nickel zinc ferrite (NZF) as a magnetic nanofiller. Two commercially available MWCNTs, each with a distinctly different aspect ratio of 115 and 315, were chosen to represent the regimes of low and high aspect ratios of the dielectric fillers. This study aims to evaluate the comparative influence of aspect ratio variation on the electromagnetic absorption behavior rather than establishing a full parametric optimization curve. An E-glass fiber with a 12 K designation was used to ensure the sufficient strength of the composite. The weight percentage of NZF was set to 20% and that of MWCNTs (0.5-2%) based on previous studies, as this combination demonstrated effective microwave absorption [7,17]. The maximum weight percentage of MWCNTs was limited to 2% to avoid agglomeration during sample fabrication.

Initially, the nanofillers were mixed with acetone and heated to 80 °C to completely evaporate the acetone. The mixture was combined with the epoxy resin and ball-milled for 60 min at 500 rpm to obtain the nanocomposite. The hardener was incorporated at a 100:24 ratio and subjected to sonication using a bath-type sonicator at 90 kHz for 30 min. The speed and duration of ball milling and sonication were selected from the initial optimization trials aimed at obtaining a uniform dispersion and avoiding agglomeration. The composites were prepared using the hand lay-up method with the help of two heavy steel plates and spacers. Initially, the steel plate surface was cleaned with a releasing agent for easy demoulding. The E-glass fiber was impregnated with the premixer by placing it on a plate and uniformly applying the coating. Rollers were used to release the entrapped air. After obtaining the desired stack of layers, the composite laminates were sandwiched between steel plates using spacers. Then these samples were cured for total 6 h at stepwise temperatures (60 °C → 120 °C → 170 °C) in a hot-air oven. They were machined to a size of 22.86 mm X10.16 mm to fit into the Vector Network Analyzer (VNA) sample holder. The details of the fabricated specimens are presented in Table 1. & Table 2. These samples had a thickness of ~2 mm, as measured using a micrometer (least count: 0.01 mm). Calibrated spacers were

employed during hand layup to ensure thickness uniformity; however, layer-wise thickness variation and statistical analysis were not performed.

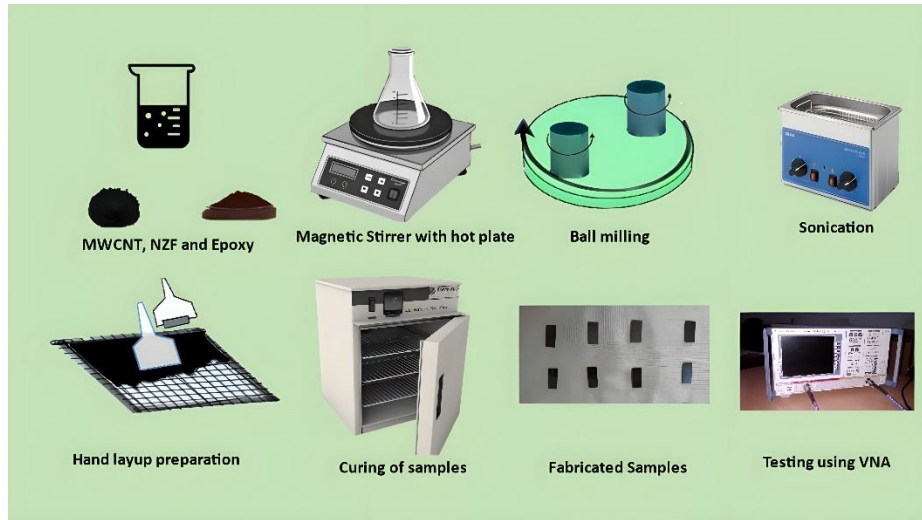


Figure 1 Nanocomposites preparation and testing

Table 1 High-aspect-ratio sample details

Sample Name	Wt % of NZF	Wt% of MWCNTs
NHM1	20	0.5
NHM2	20	1
NHM3	20	1.5
NHM4	20	2

Table 2 Low-aspect-ratio sample details

Sample Name	Wt % of NZF	Wt% of MWCNTs
NLM1	20	0.5
NLM2	20	1
NLM3	20	1.5
NLM4	20	2

The structure and size of the low- and high-aspect-ratio MWCNTs and nickel zinc ferrite were analyzed using scanning electron microscopy (SEM). The EM characteristics of the fabricated specimens were assessed using a vector network analyzer (VNA) (ZVB 20, Rohde & Schwarz) with a waveguide setup in the X-band. The VNA was calibrated before measuring the complex permittivity and permeability by the Thru Reflect Line (TRL) method using calibration kits provided by the manufacturer. Dielectric property measurements using the VNA were performed by assuming plane-wave normal incidence on a homogeneous, isotropic, single-layer absorber with uniform thickness and Perfect Electrical Conductor (PEC) backing. The complex permittivity and permeability obtained from these tests were averaged over three independent samples and used to evaluate the reflection loss of the trilayered radar-absorbing material using the transmission line theory. In a trilayered configuration, the layers are arranged in such a way that to gradually achieve the impedance matching condition and minimizing the reflections at air material interface.

3. Results and Discussion

3.1 Micro structural Properties of MWCNTs and Nickel Zinc Ferrite

Multi-walled carbon nanotubes have a high aspect ratio and unique structure, which are responsible for their microwave absorption capabilities. The two different types of MWCNTs considered in this study were those with high aspect ratios of 315 and those with low aspect ratios of 115. The low-aspect-ratio MWCNTs had diameter of 80-94 nm and length is 9-11 μm . The high-aspect-ratio MWCNTs had a length of 3-8 μm and a diameter of 10-25 nm. The SEM images of the two types of MWCNTs are shown in Figure 2(a) and 2(b). MWCNTs are usually bundled owing to the van der Waals forces between them. The SEM image of the nickel zinc ferrite is shown in Figure 2(c). NZF has a particle diameter of 26 nm and was synthesized using the solgel method [18]. Owing to their magnetic properties, NZF particles tend to cluster together. Figure 2(d) presents the fractured surface

morphology of the high-aspect-ratio composite, which was analyzed using SEM. The micrograph displays cylindrical E-glass fiber embedded in the polymer matrix, along with MWCNTs and NZF filler phases dispersed in the surrounding area. This image qualitatively verifies the presence of both fiber reinforcement and nanofiller integration within the matrix, suggesting successful composite formation, and there is no significant evidence of large-scale agglomeration or interfacial debonding.

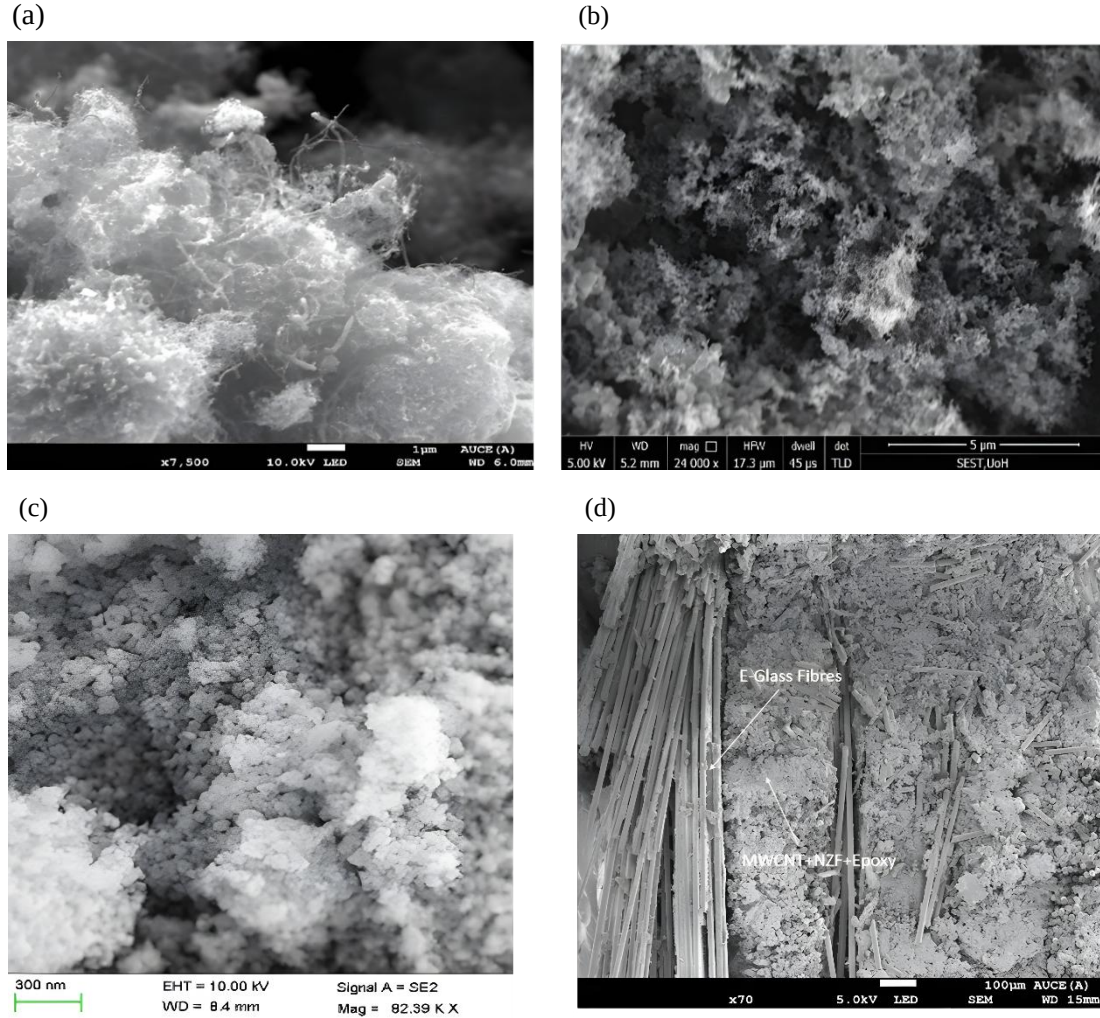


Figure 2 Micrographs of (a) Low-aspect-ratio MWCNTs (b) High-aspect-ratio MWCNTs (c) Nickel Zinc Ferrite (d) Fractured composite

3.2 The electromagnetic properties of fabricated samples

The frequency dependence of the electromagnetic properties of the prepared samples is shown in Figures 3 and 4. The real and imaginary components of the complex permittivity and permeability of the high-aspect-ratio samples are shown in Figures 3(a) and 3(b), respectively. The standard deviation of the measured electromagnetic properties was very small (within ± 0.01), indicating good repeatability; therefore, error bars were omitted from the graphs for clarity. From Figure 3(a), it is evident that the NHM4 sample exhibits real and imaginary permittivity values of 4.6 and 1.8, respectively, at 12.4 GHz. An increase in the MWCNT content from 0.5 to 2 wt% results in a corresponding increase in both the real and imaginary permittivity, with a slightly greater change in the imaginary component [19]. The complex permeability results (Figure 3(b)) indicate that the NHM1 sample exhibits real and imaginary values of 0.85 and 0.21, respectively, at 8.2 GHz. For the low-aspect-ratio samples, the complex permittivity is shown in Figure 4(a), where the NLM1 sample shows real and imaginary values of 3.2 and 0.2 at 8.2 GHz respectively. The corresponding real and imaginary parts of the complex permeability are 1.2 and 0.56 at the same frequency, respectively, as shown in Figure 4(b).

To further elucidate the underlying loss mechanisms, the dielectric and magnetic loss tangents were analyzed for both the high- and low-aspect-ratio samples. The dielectric and magnetic loss tangents are key electromagnetic parameters that govern a material's ability to absorb and dissipate incident radiation and are defined as the ratio

of the imaginary to the real parts of the complex permittivity and permeability, respectively [20–22]. Figure 5 illustrates the variations in the magnetic and dielectric loss tangents for the low-aspect-ratio samples.

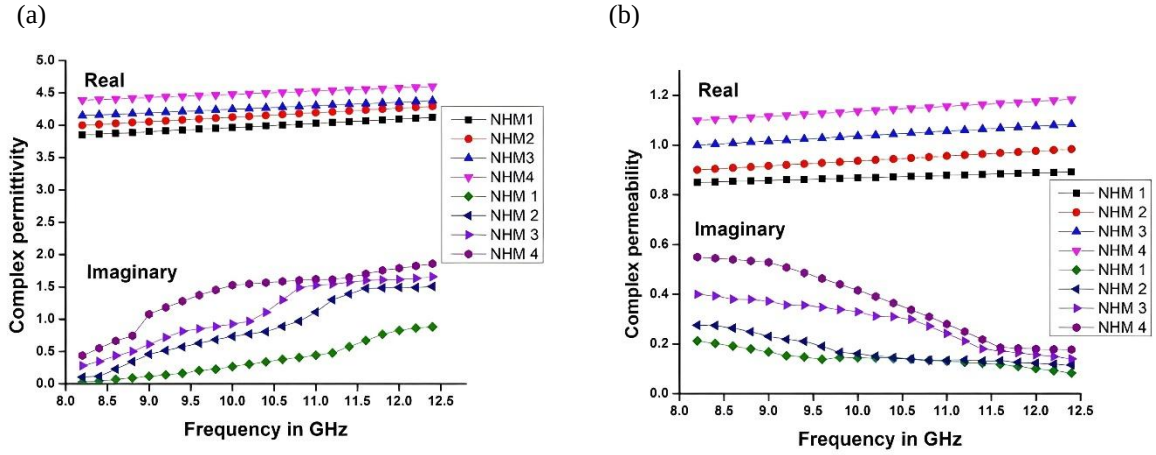


Figure 3 (a) & (b) Complex permittivity & complex permeability of high-aspect-ratio samples

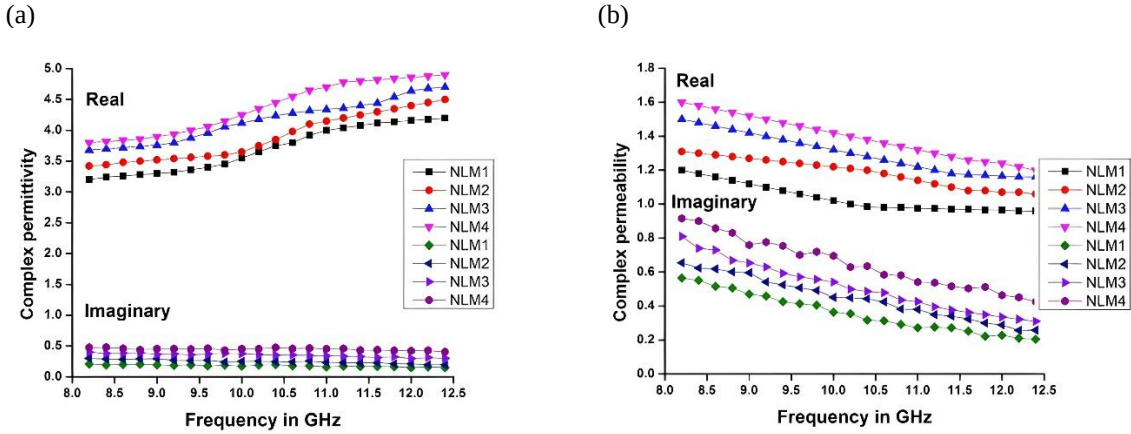


Figure 4 (a) & (b) Complex permittivity & complex permeability of low-aspect-ratio samples

The values depicted are influenced by the frequency and exhibit considerable differences in the magnetic loss values throughout the X band. The dielectric loss tangent values of the low-aspect-ratio samples ranged from 0.05 to 0.12, whereas the magnetic loss tangents varied from 0.21 to 0.57, respectively. Notably, sample NLM4 exhibits the highest magnetic and dielectric loss tangents (0.12 and 0.57) at 8.2 GHz, whereas NLM1 shows the lowest values (0.05 and 0.21) at 12.4 GHz, indicating a strong dependence on the MWCNTs composition. The magnetic and dielectric loss tangents of the high-aspect-ratio samples are presented in Figure 6. The dielectric loss tangents ranged from 0.01 to 0.4, whereas the magnetic loss tangents varied from 0.25 to 0.5. Among the samples, NHM4 exhibits the highest dielectric and magnetic loss tangents (0.4 and 0.5), whereas NHM1 exhibits the lowest values (0.01 and 0.25). These variations were directly proportional to the weight percentage of MWCNTs at a constant thickness. A similar trend was observed for the samples with low aspect ratios.

The significant variation in the loss tangents of NHM4 and NLM1 can be explained by the electromagnetic percolation theory, which states the importance of the high aspect ratio of fillers in microwave absorption. According to this theory, the filler material in the polymer matrix should possess a high conductivity and aspect ratio to easily form a conductive network and reach the percolation threshold at a low concentration of a conductive filler [23]. The formation of conductive networks in high-aspect-ratio MWCNTs, characterized by their long length relative to their diameter, creates conductive pathways through physical contact and tunnelling mechanisms within polymer matrices. The high dielectric loss also leads to enhanced microwave absorption owing to interfacial polarization. This is caused by the larger surface area because most of the active atoms are present on the surface [2]. The influence of the E-glass fiber on the electromagnetic properties is considered negligible compared to that of MWCNTs and NZF, as it primarily acts as a low-loss dielectric reinforcement.

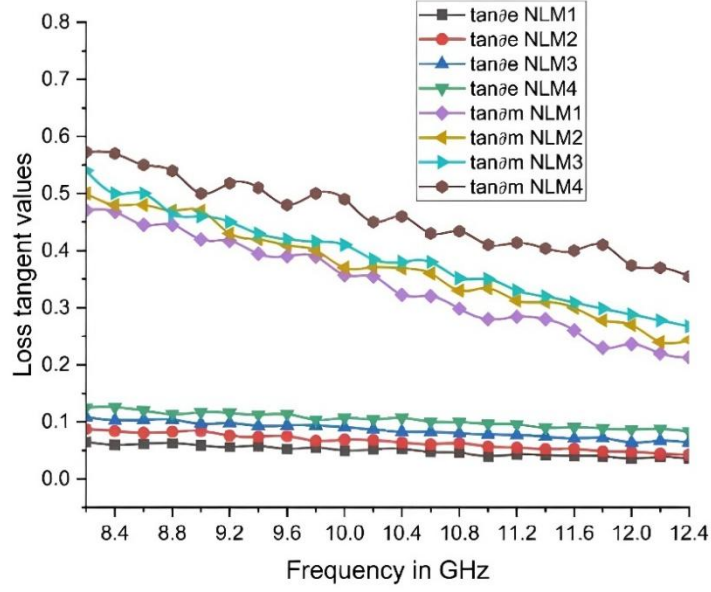


Figure 5 Loss tangents of low-aspect-ratio samples

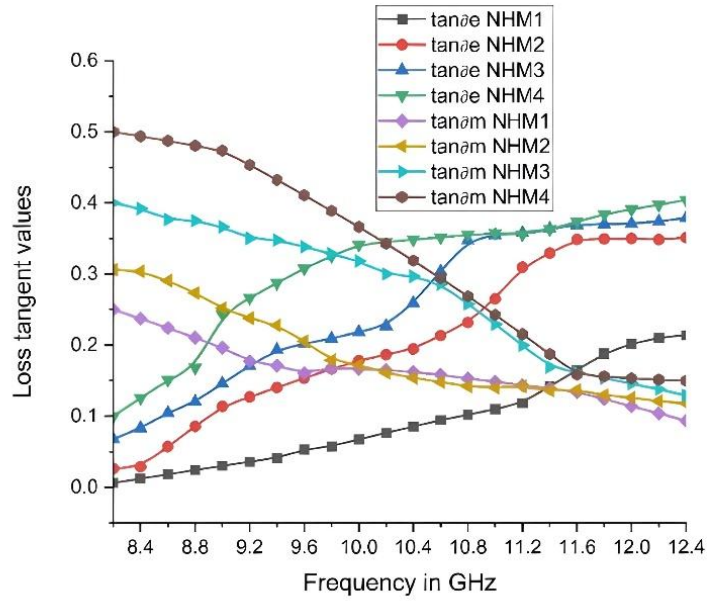


Figure 6 Loss tangents of high-aspect-ratio samples

3.3 Reflection loss of trilayered MWCNT/NZF RAMs

The enhancement of microwave absorption is achieved through the stacked-layered structure of radar-absorbing materials, which is attributed to the loss properties of the filler materials and multiple reflections [16]. The front layer of the multi-layered RAM is anticipated to provide optimal impedance matching, whereas the absorbing layers are intended to maximize the dissipation of microwave energy. The final layer is expected to emulate actual operational conditions, specifically functioning as a Perfect Electric Conductor (PEC). The attenuation constant of the absorbing layers can be evaluated using the following relation [20,24]:

$$\alpha = \frac{\sqrt{2}\pi f}{c} * \sqrt{(\mu''\epsilon'' - \mu'\epsilon')^2 + \sqrt{(\mu''\epsilon'' - \mu'\epsilon')^2 + (\epsilon'\mu'' + \epsilon''\mu')^2}} \quad (1)$$

Here, α , f , c , μ' , ϵ' , μ'' , ϵ'' are the attenuation constant, frequency, velocity of light, and real and imaginary parts of the complex permeability and permittivity respectively.

Different possible trilayered RAMs with low and high aspect ratios of MWCNTs with a thickness of 1 mm in each layer and PEC as the last layer were analyzed using the measured electromagnetic properties of the MWCNT/NZF samples. The details of the specimens are presented in Tables 3 and 4 respectively. The reflection loss of the multi-layered nanocomposites was determined using transmission line theory, as expressed in Equation [5].

$$RL = 20 \log \left| \frac{(Z_i - Z_a)}{(Z_i + Z_a)} \right| \quad (2)$$

Here Z_i indicates the first air-absorber interface input impedance and Z_a indicates the free-space impedance. The impedance of the input wave for each layer i in the multi-layered structure is expressed as follows:

$$Z_i = \eta_i \left\{ \frac{(Z_{i+1} \cos k_i t_i + j \eta_i \sin k_i t_i)}{(\eta_i \cos k_i t_i + j Z_{i+1} \sin k_i t_i)} \right\} \quad (3)$$

where t_i and η_i denote the thickness and intrinsic impedance of the i^{th} layer respectively. K_i which is known as wave number is given by

$$k^2 = 2\pi f^2 \mu_0 \epsilon_0 \mu_{ri} \epsilon_{ri} \quad (4)$$

Here μ_{ri} and ϵ_{ri} represents the relative permeability and permittivity of the i^{th} layer, f represents the wave frequency, μ_0 and ϵ_0 denote the free space permeability and permittivity.

Table 3 High-aspect-ratio RAM details

Sample Name	Layer 1	Layer 2	Layer 3
HRAM1	NHM1	NHM2	NHM3
HRAM2	NHM1	NHM2	NHM4
HRAM3	NHM1	NHM3	NHM4

Table 4 Low-aspect-ratio RAM details

Sample Name	Layer 1	Layer 2	Layer 3
LRAM1	NLM1	NLM2	NLM3
LRAM2	NLM 1	NLM2	NLM4
LRAM3	NLM1	NLM3	NLM4

The reflection loss characteristics of the high-aspect-ratio and low-aspect-ratio radar-absorbing materials under incident electromagnetic waves are presented in Figure 7. The varying bandwidths observed for all the RAMs were due to differences in their frequency dependant absorption capabilities. Among the high-aspect-ratio samples, HRAM3 with a thickness of 3 mm exhibited a reflection loss (RL) below -10 dB over the frequency range of 8.6–12.2 GHz within the X-band, corresponding to approximately 90% absorption. In comparison, HRAM2 and HRAM1 exhibit effective absorption bandwidths of 3.2 and 3 GHz, respectively, for the -10 dB criterion. The broader bandwidth observed for HRAM3 indicates its superior absorption performance. This enhancement can be attributed to its trilayered configuration, where the first layer (NHM1), identical across HRAM1, HRAM2, and HRAM3, facilitates comparable impedance matching at the air-material interface. In contrast, the second and third layers in HRAM3 consist of NHM3 and NHM4, which exhibit higher dielectric and magnetic loss tangent values, as evident from Figure 6. This combination promotes a more effective dissipation of electromagnetic energy than the other composite configurations. Table 5 presents a comparison between the performance of HRAM3 and previously reported results.

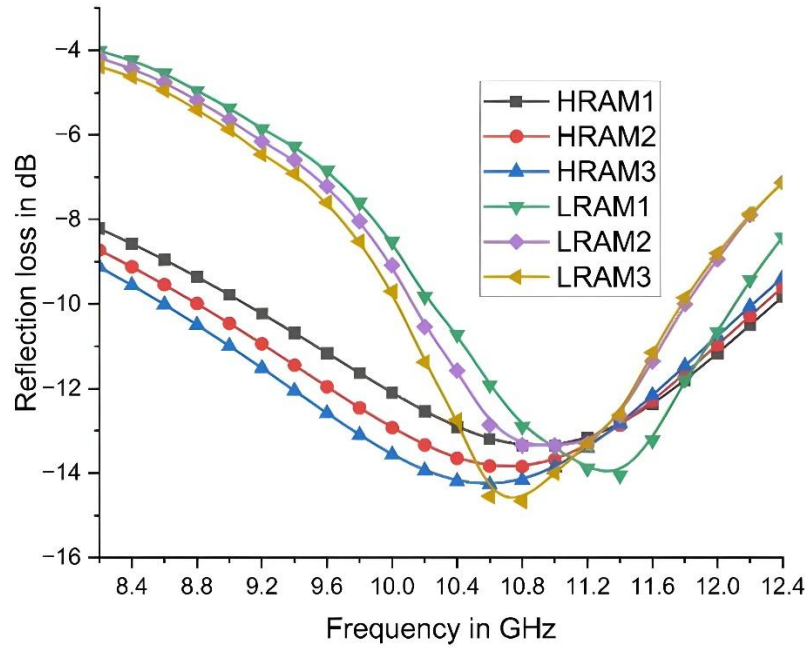


Figure 7 Microwave Absorption of hybrid nanocomposites

In the present work, the low-aspect-ratio samples demonstrated relatively narrow absorption characteristics. LRAM1 and LRAM2 exhibited a reflection loss of -10 dB over a bandwidth of approximately 1.2 GHz, whereas LRAM3 exhibited a maximum reflection loss of -14 dB at a central frequency of 10.2 GHz and maintained a reflection loss below -10 dB over the 10.2 – 11.8 GHz range. To further understand the influence of the aspect ratio on microwave absorption, the attenuation constant values of the absorber layer were calculated using Equation (1). HRAM exhibited a higher attenuation constant of 634 compared to 611 for LRAM. Although the variation in the attenuation constant was modest, the enhanced absorption could not be attributed to attenuation alone. This is likely associated with improved wave penetration into the absorber. Furthermore, the increased interfacial polarization owing to the high aspect ratio of the MWCNTs contributes to enhanced microwave attenuation [3,5].

The microwave absorption mechanism of the MWCNT/NZF nanocomposites, illustrated in Figure 8, was strongly influenced by the aspect ratio of MWCNTs. The high-aspect-ratio MWCNTs facilitated the formation of more effective conductive networks within the epoxy matrix, resulting in enhanced conduction loss and dipolar polarization of the composite. This is consistent with the higher dielectric loss tangent values observed for the high-aspect-ratio sample. Furthermore, the increased length and surface area of the high-aspect-ratio MWCNTs promoted stronger interfacial interactions with the epoxy matrix and NZF particles, leading to enhanced interfacial polarization. In contrast, low-aspect-ratio MWCNTs form less efficient conductive pathways and exhibit reduced polarization effects, resulting in comparatively lower loss tangent values and diminished microwave absorption performance [25].

Table 5 Comparison of RL values of HRAM3 with reported literature data

S. No.	Ref.	Materials	Thickness (mm)	Filler wt %	Bandwidth (GHz) @dB	Maximum R.L(dB)@ GHz
1	[25]	MWCNT/BT/PU	1.1	30	1.6 @10	-37.2 @14
2	[22]	RGO/Fe ₂ O ₄ / Paraffin	4	20	3.9 @10	-23.09@9.16
3	[17]	PMWCNT/MNZF/ Epoxy	3	2.5+20	3 @10	-29 @ 10.9
4	[7]	MWCNT/NiFe/ Epoxy	4	0.5 +15	1.6 @12	-19 @ 8.2
5	[26]	CF/Fe/Epoxy	4.2	30	4.5 @10	-16.2@ 6.1
6	[6]	MWCNT/NZF/Epoxy	3	60	1.24 @10	-19.3@8.46
7	Present work (HRAM3)	MWCNT/NZF	3	2 +20	3.6 @10	-14@ 10.8

In addition to their electromagnetic performance, glass-fiber-reinforced polymer composites are known for their superior strength and durability. The incorporation of MWCNTs has been reported to further enhance the mechanical stiffness and multifunctional performance of these composites by improving the load transfer and network formation [27,28]. However, the present study specifically focused on the electromagnetic absorption behavior. Comprehensive environmental durability testing and mechanical characterization under service

conditions will be conducted in future studies. In this study, the composites were prepared using a simple and cost-effective hand layup method. However, expanding manufacturing requires careful control of filler dispersion, layer uniformity, and interfacial bonding to maintain consistent electromagnetic properties. Challenges such as nanoparticle agglomeration and thickness variation during manual processing may impact reproducibility, indicating the need for process optimization for the industrial-scale production of radar-absorbing materials.

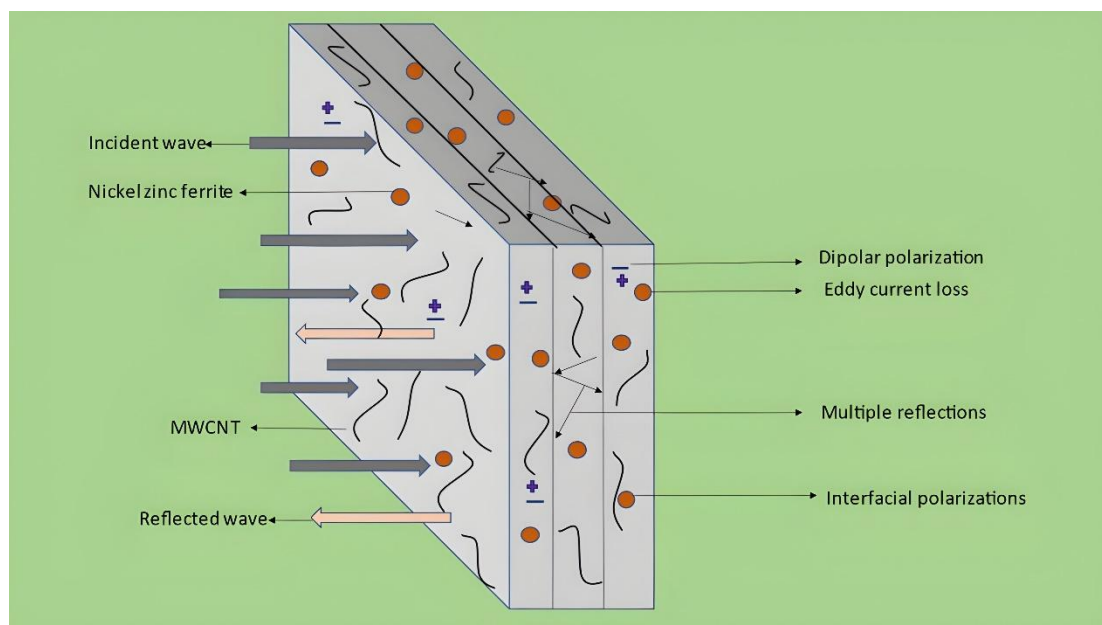


Figure 8 Possible Absorption Mechanism in multi-layered hybrid RAM

4. Conclusions

In this study, we investigated the effect of the aspect ratio of MWCNTs on the X-band microwave absorption properties of multi-layered MWCNT/NZF nanocomposites. The two different aspect ratios of the MWCNTs considered in this study were 115 and 315, respectively. The higher dielectric and magnetic loss tangents observed in the high-aspect-ratio samples led to more effective electromagnetic energy dissipation. As a result, the trilayered high-aspect-ratio composite demonstrated superior broadband absorption at equivalent thickness and filler loading, highlighting the critical role of the MWCNTs aspect ratio in enhancing the microwave attenuation performance. These findings highlight the importance of the aspect ratio of MWCNTs as an effective design parameter for developing lightweight, broadband radar-absorbing materials, offering a pathway to enhance the absorption performance through structural optimization rather than increasing the filler content. Therefore, the developed composites are promising for applications such as electromagnetic interference shielding and microwave absorption in lightweight structures. However, this study is limited to two MWCNTs aspect ratios and the X-band frequency range. The absorption performance was evaluated using transmission line theory, and the experimental validation of the multi-layer structures further strengthened the results. The hand layup process may introduce minor variations in layer thickness and filler distribution. These limitations also provide directions for future work aimed at extending the range of aspect ratios, validating the multi-layer design experimentally, and improving the fabrication consistency and long-term performance.

5. Ethical Approval

This study did not involve human participants or animal experiments; therefore, ethical approval was not required.

6. Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors used Paperpal to assist with language editing and improvement of grammar and readability. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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8. Author Contributions

Siva Nagasree Puppala: - Conceptualization, methodology, writing original draft preparation, validation; Indira Vishnu Vandana Kodey: - formal analysis, Software, Supervision; Hima Gireesh Chigurupalli- writing - reviewing and editing, and visualization

9. Conflict of interest

The authors declare no conflict of interest.

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