



Review Article

Stealth Revolution: Advancing Equipment Performance with Nano Metal-Oxide Radar Absorbing Materials

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Abstract— Over the years, microwave-absorbing materials have attracted major interest because of their critical roles in stealth, communication, and information-processing technologies. Advances in nanomaterial functionalization enable tailored dielectric and magnetic properties, with absorption governed by dielectric loss, magnetic loss, and their coupling. The article expounds on measurement principles, encompassing essential analyses, performance assessments, and prevalent interaction pathways like Debye relaxation. Notably, it showcases advancements and evaluates performance in microwave absorption using metal-oxide nanomaterials. This work provides an introduction to the basic principles of microwave absorption and summarizes recent progress in improving the absorption performance of various nano metal oxides.

Keywords— Dielectric loss; Magnetic loss; Metal-oxides; Microwave absorption; Nanomaterials

1. INTRODUCTION

In recent decades, the scientific community has observed a remarkable surge in the advancement of nanomaterial, with studies exploring their synthesis, creation, characteristics, and practical application [1-10]. The intrinsic properties of nanomaterials, which stem from their scale and are absent in larger macro-scale materials, have garnered substantial research attention, fueling widespread interest. These distinct properties of nanomaterials have brought about a transformative impact on material performance across various application domains, leading to the unveiling of novel research areas [11-17]. The minute size of nanomaterials has facilitated the attainment of expansive surface areas, giving rise to unexpected material attributes. In this context, surface effects that are nearly insignificant in bulk materials become greatly amplified to a significant degree, a phenomenon often referred to as "magnifying effects" in the literature. Surface atomic components typically exhibit unsaturation and contain numerous sites where

nanomaterials become chemically active. This results in heightened chemical reactivity, reduced melting points, and structural as well as thermal instability. These factors give rise to markedly increased chemical activities, lower melting points, and the emergence of structural and electronic deficiencies, thereby inducing unconventional optical and electronic properties [18-20]. Additionally, the limited dimensions of nanomaterials restrict the movement and excitations of charges within the materials. This results in discrete electronic structures instead of continuous ones and causes sudden shifts in optical spectra. These phenomena are referred to as quantum confinement effects. They manifest when the nanomaterials' size approaches the scale of the Bohr radius for semiconductor nanoparticles. Another similar effect is the surface plasmon resonance, observed when the size corresponds to optically-induced charge displacements in metal nanoparticles [21-24]. The investigation of nanomaterials intriguing properties has led to significant advancements in fields

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such as optics, quantum devices, photocatalysis, photovoltaics, and more [25-27]. However, the specific use of nanomaterials as radar absorbing materials for defense applications has not yet been studied in an integrated manner. Most research focuses on the basic properties of materials or microwave absorption mechanisms separately, without linking them to the practical needs of stealth technology [16]. In addition, systematic comparisons between various nanometal-oxides, dielectric and magnetic loss mechanisms, and the effectiveness of synthesis methods are still limited. Therefore, this review is important to integrate the latest developments and direct the development of nanometal-oxides to support more effective and applicable radar absorbent material innovations.

2. MECHANISM OF MICROWAVE ABSORPTION

Microwave incidents occur when an oscillating electric field and magnetic field become intertwined. Substances that cause absorption of microwaves achieve this by engaging with either field, or even both [28]. This prompts the interaction between light and matter within the gigahertz range of the electromagnetic spectrum. This behavior complies with Maxwell's equations, wherein disturbing one of the electromagnetic fields via interaction with a material substance will cause a corresponding alteration in the other field, ultimately leading to the dissipation of the entire electromagnetic wave [29]. The phenomenon of dielectric loss originates from the distinct electronic interplay between the electric field of the incoming electromagnetic radiation and the nanomaterial, leading to reflection loss [30]. As a consequence, magnetic loss represents the unique magnetic interconnection between the nanomaterial and the electromagnetic wave [31]. Among the numerous distinct action mechanisms detailed in various sources, each can fundamentally be categorized as primarily arising from electronic interactions, mostly stemming from magnetic interactions, or a combination of both. These interactions, along with the inherent attributes of the nanomaterial, lead to the attenuation of microwave radiation during its engagement with a material medium. Utilizing Maxwell's equations and the resultant constitutive relationships derived from these equations, it becomes evident that a nanomaterial's reactions to an incoming electromagnetic wave are fundamentally shaped by the nanomaterial's intrinsic bulk permittivity and permeability. In this context, permittivity and permeability are represented as complex values in order to encompass energy storage and dissipation effectively [32].

This in-depth understanding of the mechanisms of dielectric and magnetic loss not only has theoretical implications, but also serves as a key foundation in the development of modern stealth technology. In radar systems, the effectiveness of an absorbent material is determined by its ability to achieve impedance matching between the material and free space, so that electromagnetic waves are not reflected but are absorbed and dissipated as heat energy. This principle has been extensively discussed in radar absorbing

materials (RAM) studies, where the parameters of complex permittivity and complex permeability, directly determine the value of reflection loss (RL) and absorption bandwidth (Eq. 1 and Eq. 2) [33].

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1)$$

$$\mu = \mu' - j\mu'' \quad (2)$$

The stealth revolution occurs when materials engineering at the nanoscale allows precise control of those electromagnetic parameters. Nano metal-oxides, such as Fe_3O_4 and $\alpha\text{-Fe}_2\text{O}_3$, exhibit increased interface polarization, dipole relaxation, and magnetic resonance that significantly improve the energy loss mechanism and improve impedance matching at the GHz frequency [34]. This approach shifts the stealth paradigm from a mere geometric design of cross-section radar (RCS) reducers to advanced electromagnetic material engineering capable of producing high RL values, wide bandwidth, as well as thinner and lighter layer thickness.

2.1. Dielectric Loss

The dielectric loss factor is a measure of the energy absorbed within a medium as electromagnetic waves pass through it. Under ideal conditions, loss is zero and the dielectric loss factor is also zero. Dielectric loss represents the characteristic electronic nature, specifically the interaction between the electric field of incident electromagnetic radiation and the nanomaterial, resulting in reflection loss [35]. The dielectric loss capability of absorbent materials mainly originates from conductivity loss and polarization loss (ionic polarization, interface polarization, and electronic polarization)[36]. The energy pathway of dielectric loss is depicted as the route transmitting energy from the propagating electric field form to thermal output through interaction with the absorber material. The electric field of the electromagnetic wave propagates forward, causing a sinusoidal polarity change and orthogonal direction relative to the propagation direction. Charged entities around the wave spatially interact with the electric field, thus being drawn into the oscillatory motion of the field wave [37].

Electromagnetic waves oscillate in polarity, and their initial movement induces misalignment between the electromagnetic wave's electric field and the distribution of specific charged particles. In cases where this induces charge displacement via the electric field force, the potential generated in the medium is shifted from its original state through the movement of the electromagnetic wave. According to the theory of free electrons (Eq. 3), where ε_0 denotes the dielectric constant in a vacuum, and denotes electrical conductivity. High electrical conductivity will result in a high dielectric constant, indicating a strong dielectric loss capability. However, material conductivity cannot be excessively high because under external electromagnetic influence, materials with high conductivity will form continuous conduction currents.

This creates impedance mismatch between the material and free space, making it a strong reflector of electromagnetic waves.

$$\varepsilon'' \approx \sigma / 2\pi\varepsilon_0 f \quad (3)$$

2.2. Magnetic Loss

Magnetic loss is a characteristic of the magnetic interaction between material media and electromagnetic wave [38]. Generally, magnetic loss is typically generated from natural resonance, exchange resonance, and eddy current loss in the microwave band. Natural resonance usually occurs at lower frequencies and is related to anisotropic fields, which can be expressed by the Eq. (34). Where f_r is the resonance frequency, γ is the gyromagnetic ratio, and H_a is the anisotropic field [39]. The contribution of eddy currents to magnetic loss can be evaluated by analyzing the relationship between and frequency (Eq. 5 and Eq. 6).

$$f_r = \frac{\gamma H_a}{2\pi} \quad (4)$$

$$C_0 = \mu'' (\mu')^{-2} f^{-1} \quad (5)$$

$$C_0 = \frac{\mu''}{(\mu')^2 f} \quad (6)$$

If the value of Eq. (5) remains constant with frequency, eddy current loss will be the sole cause of magnetic loss [39]. Absorber thickness is an important parameter reflecting the intensity and position of maximum RL. When the matching thickness (T_m) changes, the matching frequency F_m of the absorber material will shift significantly [39-40]. Eddy current loss is the reason for magnetic loss under the assumption that the value of C_0 remains constant as the frequency changes. Exchange resonance exists in ferromagnetic particles, which can be symbolized by the following formula in Eq. 7.

$$f_{exc} = \frac{\gamma}{2\pi} \left(\frac{C u_{kn}^2}{R^2 M_s} + H_0 - aM_s \right) \quad (7)$$

where f_{exc} is the exchange frequency, C is the exchange constant, a is the demagnetization factor, u_{kn} is the root of the derivative of the spherical Bessel function, R is the radius of the absorber particle, while H_0 , H_a , dan γ represent the crystal magneto anisotropy field, anisotropy field, and gyromagnetic ratio.

Table 1. Key electromagnetic parameters of nano metal-oxide RAM

Aspects	Key Parameters	Main Mechanism	Impact on RAM Performance	Relevance of Metal Nano Oxides
Microwave Interactions	Maxwell's equations	Electric (E) and magnetic (H) field coupling at GHz	Attenuation occurs through the interaction of E, H, or both	Nanostructures allow simultaneous electric–magnetic responses
Response Dielectric	$\varepsilon = \varepsilon' - j\varepsilon''$	Polarization (electronics, ionic, dipole, interface) & conductivity	Increases dielectric loss and energy conversion to heat	High interface polarization due to grain limits & defects
Magnetic Response	$\mu = \mu' - j\mu''$	Natural resonance, exchange resonance, eddy current	Increases magnetic loss & absorption bandwidth	Active magnetic resonance in nanomagnetic ferrimagnetic particles
Impedance Matching	$Z_{in} \approx Z_0$	Balancen ε dan μ	Minimizes surface reflection	Composition & particle size engineering for optimal matching
Reflection Loss (RL)	RL (dB)	Functions of ε , μ , and thickness	$RL < -10$ dB \rightarrow effective absorption	Nano metal-oxide allows high RL with a thin layer
Absorbent Thickness	$\lambda/4$ matching	Maximum absorption frequency adjustment	Controlling the position of the absorption peak	Nano size allows for lightweight & thin design

2.3. Dielectric/Magnetic Loss Coupling

Maxwell's quartet of equations encompassing electricity and magnetism establish a correlation between the two fields, culminating in the concept of electromagnetic radiation as an interwoven entity. As these two fields progress forward, both perpendicular to each other and to the direction of propagation, they exhibit wave function amplitudes that maintain an equivalent magnitude throughout the propagation distance. Consequently, the reduction in intensity of one field affects the other, according to the deductions from these derivations. However, since both fields possess potential energy that can be harnessed, the attenuation

of all electromagnetic energy can occur through interactions involving either the electric component, the magnetic component, or a fusion of both. This leads to the collective outcome of absorption [41]. Provide sufficient detail to allow the work to be reproduced, which may include Materials, Instrumentation, and Procedure.

3. MEASUREMENT PRINCIPLES

Conducting practical assessments of how nanomaterials react to the electric and magnetic components of incoming electromagnetic radiation offers the possibility to engage in a series of computations aimed at quantifying the physical and experimental

characteristics of created nanomaterials. These measurement methodologies rooted in fundamental principles have been thoroughly explored in multiple technical documents from the National Institute of Standards and Technology (NIST) and in textbooks published elsewhere. Therefore, these fundamental aspects will be touched upon briefly here, as our primary focus lies in the nanomaterials that these techniques evaluate. Moreover, attention will also be limited to non-resonant analytical approaches, as these methods enable the assessment of electric and magnetic response characteristics across a spectrum of frequencies. This frequency range aligns with the central scope of the nanomaterials investigations discussed within this review.

Several electromagnetic interaction mechanisms have been distinctly clarified through experimentation or the analysis of permittivity and permeability, and will be succinctly addressed in this context. These mechanisms encompass Debye relaxation for dielectric interactions, alongside eddy current loss for magnetic interactions.

3.1. Debye Relaxation

Debye relaxation refers to the gradual return of polar molecules or particles to their original orientation after being subjected to an external electric field. This phenomenon is often observed in dielectric materials and is characterized by a time-dependent response in the polarization of the material [42-43]. Debye relaxation involves the alteration of the usual state of matter by incoming electric fields, leading to polarization through mechanisms such as the distortion of the electron cloud, localized bond distortions, or the alignment of permanent dipoles [44]. Once polarized, dipoles reposition themselves against a counteracting force, resulting in energy dissipation in the form of heat. Debye theory is used to model the relationship between polarization and frequency in this process. Derived from Debye's theory, the expression of permittivity is depicted in **Figure 1**, where f represents the frequency of the incident wave, ϵ_0 denotes the static dielectric constant approaching the limit of ϵ_R as f approaches zero, ϵ_∞ signifies the optical dielectric constant as f tends

towards infinity, and t stands for the relaxation time. This equation simplifies in the ϵ' and ϵ'' plane to assume the shape of semicircle, recognized as a Cole-Cole diagram [45].

The exponential factor "a" is a practical coefficient incorporated to accommodate shape variations. In standard scenarios, a is usually close to 0, resulting in the semicircular shape of the Cole-Cole diagram. By employing this diagram, the relaxation time τ can be deduced for a specific operating frequency using the formula in Figure 1. In this equation, β represents the gradient of a line that intersects the operating frequency point and ϵ_s , or conversely, the reciprocal of the gradient of a line passing through the operating frequency point and ϵ_∞ . Subsequently, τ can be calculated from the value of β .

3.2. Eddy Current Loss

Eddy current loss refers to the dissipation of energy that occurs when a conductive material is exposed to a changing magnetic field. This phenomenon induces circulating currents, known as eddy currents, within the material. These currents create their own magnetic fields that oppose the original changing magnetic field, leading to energy conversion into heat and resulting in energy loss. Eddy current loss is a common occurrence in various applications, such as electrical transformers, motors, and electromagnetic compatibility studies [41]. Results and discussion contain findings of research and their discussion. All findings must be supported by sufficient data. This part must answer hypothesis of the research stated in the Introduction. The actual results and discussion, supported by schemes, figures, graphs, tables, reactions, and equations. Figures, charts, tables, schemes, and equations should be embedded in the text at the point of relevance. All Tables and figures must have a title or caption and a legend to make them self-explanatory. In addition, the equation should be written using the equation editor.

4. NANO METAL-OXIDES FOR MICROWAVE ABSORPTION

4.1. Iron Oxides

Margins Iron oxides have garnered significant interest as effective microwave absorbers due to their unique electromagnetic properties and versatile applications.

This literature review delves into the exploration of iron oxides' utilization as microwave absorbers and their implications across various fields. Iron oxides, including magnetite (Fe_3O_4) and hematite ($\alpha\text{-Fe}_2\text{O}_3$), possess intrinsic magnetic properties that facilitate the absorption of electromagnetic radiation, particularly in the microwave frequency range. In the context of this study, the nanoparticle shape of magnetite and hematite was obtained through synthesis using a coprecipitation method that allows control of particle size at the nanometer scale. The method produces nanomaterials with a high surface area and uniform particle distribution, thereby improving electromagnetic interactions with

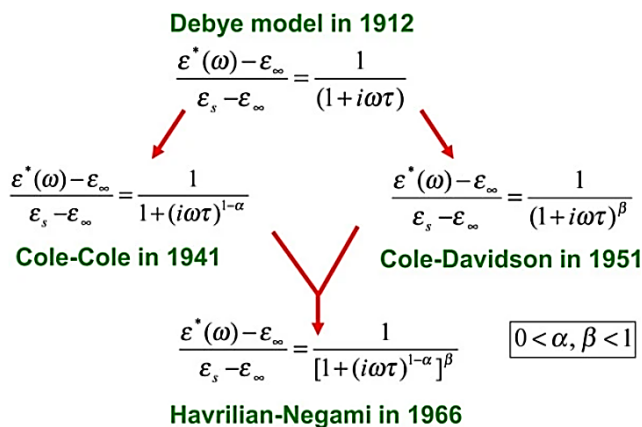


Figure 1. Evolution map for Debye, Cole-Cole, Cole-Davidson, and HN model.

microwaves. The interaction between the incident microwaves and the iron oxide nanoparticles induces eddy currents and magnetic losses, leading to the conversion of electromagnetic energy into heat. The method produces nanomaterials with a high surface area and uniform particle distribution, thereby improving electromagnetic interactions with microwaves [46]. The interaction between the incident microwaves and the iron oxide nanoparticles induces eddy currents and magnetic losses, leading to the conversion of electromagnetic energy into heat. Understanding the underlying absorption mechanisms is crucial for optimizing the design and performance of iron oxide-based microwave absorbers.

Liu et al (2007) produced a collection of Fe₃O₄ core/shell nanoparticles and nanosheets through the calcination of α -Fe₂O₃ in acetone. They investigated the electromagnetic characteristics of these materials by analyzing their permittivity and permeability. The resulting nanomaterial exhibited significant magnetic interaction at lower frequencies but approached a trivial outcome of nearly $\mu_r = (1 + 0i)$ at higher frequencies. It was in this higher frequency range where the highest RL values were predominantly observed, notably with nanomaterials like 60 nm Fe₃O₄@C nanosheets achieving RL values of approximately -41.9 dB at 12.8 GHz with a material thickness of 2.0 mm

The nanosize of the radar-absorbing material improves absorption performance due to the higher specific surface area and greater number of grain boundaries, thus strengthening the interaction of electromagnetic waves with the material. This increase in surface area leads to more active sites that can interact directly with incoming electromagnetic waves, making the energy dissipation process more effective. The structure of the nanoparticles also improves the dielectric and magnetic loss mechanisms through interface polarization, magnetic domain resonance, as well as better impedance matching at high frequencies. The combination of these effects results in increased reflection loss and greater absorption bandwidth than micro-sized materials [16]. In addition, size control at the nanoscale allows for the optimization of relaxation mechanisms and uniform particle distribution, which has been shown to significantly improve the efficiency of radar absorbing materials [47].

4.2. Manganes Oxides

The utilization of manganese oxides as microwave absorbers has been a subject of extensive research due to their unique electromagnetic properties and potential applications across various fields. This literature review examines the current understanding of manganese oxides' role as microwave absorbers and their implications in diverse domains.

Manganese oxides, including various forms such as MnO, MnO₂, and mixed-valence manganese oxides, exhibit intriguing electromagnetic properties that make them suitable for microwave absorption applications [42]. The absorption mechanism involves the interaction between incident microwaves and the crystal structure

of manganese oxides, leading to the conversion of electromagnetic energy into heat through dielectric loss and magnetic loss processes. Understanding the fundamental absorption mechanisms is essential for optimizing the microwave absorption performance of manganese oxide-based materials.

The successful utilization of manganese oxides as microwave absorbers relies on tailoring their morphology, crystallinity, and composition through precise synthesis and engineering approaches. Techniques such as hydrothermal synthesis, sol-gel methods, and chemical vapor deposition enable the control of manganese oxide nanostructures and surface characteristics, thereby influencing their microwave absorption properties. Furthermore, doping with transition metals or incorporating carbonaceous additives can enhance the microwave absorption efficiency and broaden the absorption bandwidth of manganese oxide-based absorbers.

Additional investigations into manganese oxide nanomaterials and compounds like urchinlike α -MnO₂, Mn₃O₄, and La:Sr/MnO₃ have revealed substantial returns in the gigahertz spectrum. The manganese species present in these materials exhibited a tendency to provoke dielectric interaction, while the La:Sr dopants exhibited an enhanced response to both dielectric and magnetic interactions in tandem.

Manganese oxides represent a versatile class of microwave absorbing materials owing to their tunable composition, rich valence states, and adaptable nanostructures. Through controlled synthesis, morphology engineering, and strategic doping or hybridization, their dielectric and magnetic responses can be optimized to achieve enhanced attenuation capability and broader bandwidth in the GHz range. These advantages position manganese oxide-based systems as promising candidates for next-generation radar absorbing applications.

4.3. Titanium Oxides

Titanium oxides, including titanium dioxide (TiO₂) and other titanium oxide phases, exhibit intriguing electromagnetic properties that enable efficient absorption of microwave radiation. The absorption mechanism involves interactions between incident microwaves and the crystal structure of titanium oxides, leading to the conversion of electromagnetic energy into heat through dielectric loss and magnetic loss processes. Understanding these fundamental absorption mechanisms is critical for optimizing the microwave absorption performance of titanium oxide-based materials.

Titanium oxide-based microwave absorbers find wide-ranging applications in electromagnetic interference (EMI) shielding and radar absorption materials for telecommunications, aerospace, and defense systems. By attenuating incident electromagnetic waves, these materials mitigate EMI-related issues and ensure the reliable operation of electronic devices and sensitive equipment. The tunable electromagnetic properties of titanium oxides offer

opportunities for customizing EMI shielding materials to meet specific application requirements and regulatory standards.

Recent advancements in nanocomposite materials have facilitated the development of multifunctional titanium oxide-based composites with enhanced microwave absorption capabilities. Incorporating titanium oxides into polymer matrices or nanostructured substrates allows for synergistic effects that amplify microwave absorption efficiency while maintaining mechanical strength and thermal stability. The design and fabrication of nanocomposite architectures enable the tailoring of absorption characteristics for diverse microwave absorption applications.

Additionally, mesoporous carbon/TiO₂ composites have been found to yield desirable RL values at significant thicknesses, with the 9.0 mm composite, composed of equal proportions, showcasing a remarkable -53.8 dB RL at 12.1 GHz. Furthermore, complex titanium-derived oxides like barium titanate have been combined with dopants and structural defects to induce microwave absorption. Jing et al. observed the electromagnetic characteristics of flake BaTiO₃, revealing high permittivity values associated with the synthesized nanomaterials. The highest recorded RL value was -29.6 dB at 12.0 GHz with a 4.0 mm thickness.

Titanium oxides provide a flexible platform for microwave absorption due to their adjustable dielectric behavior, structural stability, and compatibility with composite design. Through nanostructuring, defect engineering, and incorporation into hybrid architectures, their attenuation capability and impedance matching can be significantly improved. These features make titanium-oxide-based materials strong candidates for advanced radar absorption and EMI shielding technologies.

4.4. Zinc Oxides

Shown Zinc Oxide (ZnO) is one of the most extensively studied semiconductor materials, possessing a wide direct band gap of 3.37 eV and an exciton binding energy of 60 meV [43]. Nano-sized ZnO materials have garnered attention due to their intriguing electrical, mechanical, chemical, and optical properties, attributed to surface and quantum confinement effects. ZnO-NPs (nanoparticle size) offer significant advantages for catalytic reaction processes due to their large surface area and high catalytic activity. This metal oxide exhibits characteristics such as non-toxicity, environmental friendliness, and corrosion resistance.

ZnO is also widely used in the biomedical field for its non-toxic, biocompatible, and flexible properties [44]. Furthermore, ZnO has other advantages, including synthesis at relatively low temperatures, controllable morphology, and size-dependent properties. Nano-scale ZnO exhibits distinct properties compared to its bulk counterpart. Currently, there are two main synthesis routes: dry and wet processes. However, wet processes such as hydrothermal, solvothermal, and sol-gel methods are preferred due to the ease of parameter control and relatively low cost. In these processes, particle size control is typically achieved by controlling

the calcination temperature [48]. However, due to its high surface energy, agglomeration often occurs, necessitating the addition of capping agents.

The production of pure ZnO nanomaterials requires challenging preparation and morphology control, which can be further developed for various applications. Its unique physical and chemical characteristics, coupled with excellent chemical stability, render ZnO suitable for numerous potential applications in photoluminescence, photocatalysis, infrared stealth technology, and antibacterial activity [49]. Moreover, ZnO exhibits distinctive magnetic properties, and its dielectric loss suggests a capability for absorbing weak microwave signals. Previous research, such as studies on ZnO nanoflowers [50], ZnO nano comb, ZnO nano trees, and crossed ZnO netlike microstructure has shown that modulating the size, structure, and morphology of ZnO can enhance its electromagnetic wave absorption properties.

4.5. Nickel Oxides

Nickel oxides, including various phases such as NiO and Ni₂O₃, possess intriguing electromagnetic properties that make them suitable candidates for microwave absorption. The absorption mechanism involves interactions between incident microwaves and the crystal structure of nickel oxides, leading to the conversion of electromagnetic energy into heat through dielectric and magnetic loss processes. Understanding these fundamental mechanisms is crucial for optimizing the microwave absorption performance of nickel oxide-based materials [51].

The successful implementation of nickel oxides as radar absorbing materials relies on precise synthesis methods and engineering approaches to tailor their morphology, composition, and electromagnetic behavior. Various techniques, including sol-gel processes, hydrothermal synthesis, and chemical vapor deposition, enable the controlled fabrication of nickel oxide nanostructures with desired radar absorbing properties. Doping with other elements and controlling the crystalline structure further enhances the radar absorption efficiency and broadens the absorption bandwidth of nickel oxide-based RAMs.

Nickel oxides offer considerable promise as microwave absorbing materials because their dielectric and magnetic responses can be tuned through morphology control, compositional adjustment, and defect engineering. With appropriate synthesis strategies and doping, Ni-based oxides can achieve improved attenuation performance and wider absorption bandwidths. Consequently, they remain attractive candidates for advanced radar absorbing and electromagnetic management applications.

It can be concluded that absorption efficiency is governed by the synergistic interplay between dielectric relaxation (Debye mechanisms), magnetic resonance, eddy current loss, interfacial polarization, and nanoscale structural engineering rather than by intrinsic composition alone. Iron oxides (Fe₃O₄/α-Fe₂O₃) exhibit

Table 2. Comparison of nano metal-oxide systems for radar absorbing applications

Oxide System	Dominant Loss Mechanism	Strength	Main Limitation
Fe ₃ O ₄ / α-Fe ₂ O ₃	Magnetic + dielectric coupling	Strong magnetic resonance; good impedance balance	Magnetic response decreases at high GHz
MnO _x	Mainly dielectric (polarization)	Tunable valence states; strong interfacial polarization	Weak intrinsic magnetism
TiO ₂ -based	Dielectric dominant	High permittivity; stable structure	Requires thicker layer if non-magnetic
ZnO	Dielectric (morphology-driven)	Easy morphology control; semiconductor behavior	Limited magnetic contribution
NiO-based	Tunable dielectric–magnetic	Adjustable phase & defect engineering	Moderate attenuation without doping

the most balanced performance due to their combined dielectric–magnetic coupling and favorable impedance matching, although their magnetic contribution diminishes at higher GHz frequencies. In contrast, manganese, titanium, zinc, and nickel oxides are predominantly dielectric in nature and require morphology control, defect engineering, doping, or hybrid composite formation to enhance attenuation capability and broaden absorption bandwidth. Nanoscale structuring universally improves performance by increasing surface area, grain boundaries, and polarization centers, while composite architectures such as core–shell and carbon-integrated systems demonstrate superior reflection loss values and bandwidth enhancement. Overall, optimized microwave absorption in nano metal-oxides is best achieved through rational design strategies that integrate dielectric–magnetic synergy, defect modulation, impedance matching control, and lightweight nanocomposite engineering for high-frequency applications.

5. CONCLUSION

In the development of advanced platforms, nano metal-oxide radar absorbing materials (RAMs) have emerged as a transformative solution. Materials based on nickel, zinc, titanium, and manganese oxides enable improved low observability, minimized electromagnetic signatures, and superior functional performance. By enabling improved stealth, reduced electromagnetic signatures, and adaptable performance across air, land, and sea platforms, these materials significantly enhance survivability and mission effectiveness in complex operational environments.

However, challenges persist in the practical implementation of nano metal-oxide RAMs, including material durability, scalability of production, and cost-effectiveness. Addressing these challenges demands concerted research efforts, interdisciplinary collaborations, and technological innovations. Looking ahead, the continued exploration and advancement of

nano metal-oxide radar absorbing materials hold the potential to revolutionize military equipment design, ushering in a new era of stealth technology and operational superiority. By leveraging the transformative capabilities of nano metal-oxides, military forces can stay ahead of emerging threats and maintain strategic advantage in an evolving security landscape.

6. AUTHOR'S DECLARATION

6.1. Supporting Information

There is no supporting information in this paper. The data supporting this research's findings are available on request from the corresponding author (R.Basuki).

6.2. Acknowledgements

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6.3. Conflict of Interest

There was no conflict of interest in this study.

6.4. Author Contributions

RP performed the methodology, writing original draft, review & editing. RP supervises the methodology, data analysis, and revise the manuscript. TOJT, TRY N, RH, and FZ collaborated on writing and revising the manuscript. All authors approved the final version of the manuscript.

6.5. AI Statement

AI was utilize to enhance the clarity, grammar, and overall readability of this manuscript. All technical content, data interpretation, and conclusion were solely developed and verified by the authors.

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