



Review Articles

Microwave absorbing properties of ferrites and their composites: A review

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ABSTRACT

Recently, with the quick evolution of electronic technologies, and the development of telecommunication, high-performance microwave absorbing composites in which ferrite is one of their components have attracted a lot of attention. These composites should have high absorption intensity, a wide absorption bandwidth, a thin thickness, and finally light weightness. These composites often exhibit efficiency to fulfill coveted magnetic and dielectric characteristics. This review provides a brief presentation of ferrites and among them are spinel ferrites and hexagonal ferrites. In addition to that, it discusses the classifications of ferrites according to magnetic properties, the synthesis methods to prepare nano ferrites, and control their properties. Also, it presents the main mechanism to absorb the microwaves (e.g. dielectric and magnetic losses) and finally discusses the microwave absorbing characteristics of ferrites and their composites in terms of matching frequency, reflection loss (RL) values, and absorption bandwidth.

1. Introduction

With the widespread use of microwaves, many researchers worked on studying the microwave absorption properties of many absorbent materials, as shown in Fig. 1 and that due to the increase in electromagnetic (EM) pollution as a result of the rapid advancement of wireless electronic devices and electronic systems and their use of high frequencies, in addition to new standards and rules relating to EM interference resulting from this kind of apparatuses [1–6]. Radar absorbing materials (RAMs) are significant means that we can use to concealment sensitive aims. Moreover, microwave absorbing materials (MAMs) applied vastly to prohibit and reduce EM reflections on great bodies like planes, tanks, and military equipment. Absorbent materials can be made in various shapes like coatings, sheets, and sponges [7,8]. At the beginning of the twenty-first century, new studies appeared in the field of microwave absorbers that focused on the preparation of novel nano ferrites such as hexagonal ferrites and spinel ferrites by introducing new doping elements into the structure of these materials and studying the effect of these dopings on their ability to absorb microwaves, as well. Researches have focused that nano ferrites can be synthesized by various techniques such as sol–gel, co-precipitation, microemulsion, etc. In order to obtain composites that have an elevated reflection loss, a wide absorption bandwidth, and a lightweight [9–13]. Scientific researches

are currently focused on finding novel nanomaterials more effective to absorb microwaves. Nano ferrite constitutes one of its components of the composites, such as composite materials with a nano ferrite core and a conducting polymer shell (e.g. polyaniline (PANI), Polypyrrole (PPy), etc.), and different composite materials such as (ferrite/carbon), (ferrite/graphene), (ferrite/graphene oxide), etc. The results have shown the superior microwave absorption performance of these composites compared with nano ferrite materials alone. Furthermore, they are characterized by their lightweight and relatively low thickness.

Usually, microwave absorption behaviors of the absorbent substances are determined by complex permittivity (ϵ_r) which describes the interaction of the electric field with the absorbent substance and complex permeability (μ_r) which describes the interaction of the magnetic field with the absorbent substance as illustrated in equations (1,2) [14,15].

$$\epsilon_r = \epsilon' - i\epsilon'' \quad (1)$$

$$\mu_r = \mu' - i\mu'' \quad (2)$$

The interaction of the electric and magnetic field with the absorbent substance occurs in two ways: stored power of the external electric and magnetic field in substance (real parts ϵ' , μ'), lost power because of the

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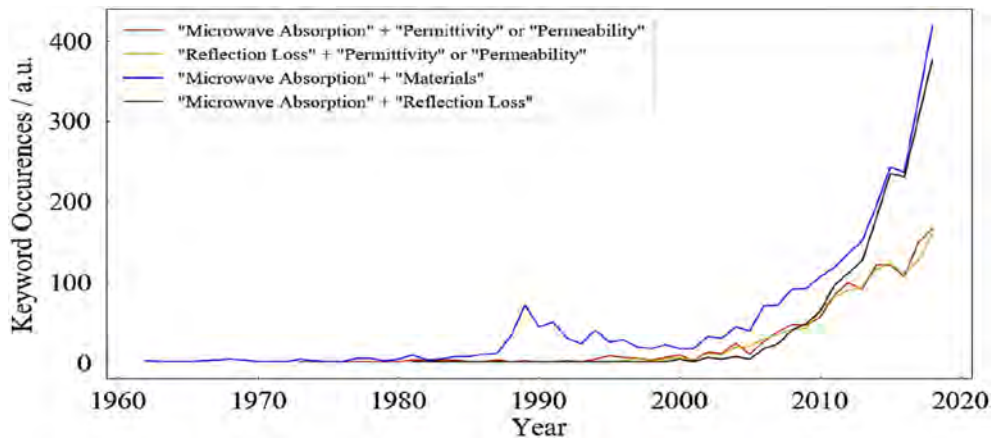


Fig 1. A curve showing the increasing trend of a number of papers reporting on microwave absorbers.

external electric and magnetic field (imaginary parts ϵ'' , μ'') [16–18].

In addition to that, dielectric loss tangent ($\tan\delta_\epsilon$) can be represented as the ratio of both ϵ'' and ϵ' by Eq. (3), and in the same way for the magnetic loss tangent ($\tan\delta_\mu$) Eq. (4).

$$\tan\delta_\epsilon = \frac{\epsilon''}{\epsilon'} \quad (3)$$

$$\tan\delta_\mu = \frac{\mu''}{\mu'} \quad (4)$$

The reflection loss expressing the EM waves absorption ability can be determined by the transmission line theory, as illustrated in the following equation [19,20]:

$$Z_1 = \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \frac{2\pi f d}{c} \sqrt{\mu_r \epsilon_r} \right] \quad (5)$$

$$RL = -20 \log \left| \frac{Z_1 - Z_0}{Z_1 + Z_0} \right| \quad (6)$$

where Z_1 and Z_0 are material impedance and air impedance, respectively. f is the frequency of EM wave, d is the absorber thickness, and c is the velocity of light.

The mechanism of reflection loss is due to firstly the dielectric loss mechanism which happens essentially from conduction loss and polarization relaxation. The ionic polarization, electronic polarization, dipole polarization, and interfacial polarization are the main source of polarization relaxation [21–24]. According to the free-electron theory, elevated electrical conductivity (i.e., low resistivity) will promote the ϵ'' and thus the conduct loss performs the main role in dielectric loss and polarization relaxation is small as shown in Eq. (7) [25].

$$\epsilon'' \approx \frac{1}{2\pi\rho f \epsilon_0} \quad (7)$$

where ρ and ϵ_0 are the resistivity and the dielectric constant of free space, respectively.

Secondly, the magnetic loss mechanism which happens essentially from natural resonance, domain wall resonance, and eddy current effect [26–29]. The natural resonance commonly occurs at a lower frequency and is linked to the anisotropic domain [30], which can be shown using equation (8).

$$f_r = \frac{\beta H_a}{2\pi} \quad (8)$$

where f_r , H_a , and β are the resonance frequency, the anisotropic field, and the gyromagnetic proportion, respectively.

In order to gain efficient EM wave absorption, there should be effi-

cient integration between dielectric and magnetic losses, so as to obtain certain impedance properties. The impedance matching (Z) property of the pattern can be calculated from Eq. (9) as the following:

$$z = \frac{z_1}{z_0} \quad (9)$$

When impedance matching is equal to or near to 1, the EM waves are not reflected on the surface of the absorbent substance and are all incident within the absorbent substance. At this period, the absolute value of the RL will arrive at the maximum value.

The attenuation of electromagnetic waves within the absorbent substance is a significant part of advanced MAMs because this attenuation constant (α) defines the dissipation characteristics of the substance as shown in Eq. (10) [31].

$$\alpha = \sqrt{2} \pi f \left[(\mu_r'' \epsilon_r'' - \mu_r' \epsilon_r')^2 + (\mu_r'' \epsilon_r' - \mu_r' \epsilon_r'')^2 \right]^{\frac{1}{2}} \quad (10)$$

It can be inferred from the attenuation constant equation that the controlling attenuation mechanisms for microwave absorption are dielectric loss and magnetic loss.

2. Purpose of the review

The purpose of this review is to present, summarize and tabulate the recent results presented in the literature for nano ferrites and their composites. In addition to that, we've highlighted the properties of spinel ferrites and hexagonal ferrites. On the other hand, we've focused on the synthetic techniques of nano ferrites and shown the advantages and disadvantages of the synthesis techniques and a discussion of the parameters impacting properties of nano ferrites.

3. Types of ferrite

Ferrites are ceramics made by blending iron (III) oxide (Fe_2O_3 , rust) with small ratios of one or more additional metallic elements. Ferrite is ordinarily given by the general formula $\text{M}-(\text{Fe}_x\text{O}_y)$, where M stands for divalent mineral ions such as (Ba, Co, Ni) [32]. Ferrites have an elevated saturation magnetization, elevated resistivity (0.1–105 $\Omega\cdot\text{m}$), and adjustable contrast range which give ferrites a preferred option in a broad field of applications. The magnetic properties of ferrite materials are the result of the magnetic moments related to the single electrons, where the magnetic properties of the atoms are determined by the number of single electrons around the nucleus, where every single electron contributes a magnetic moment resulting from its rotation around itself and around the nucleus. Ferrites can be divided into two groups depending on their magnetic coercivity [33–37]. Hard ferrites have distinguished high coercivity, so it is hard to demagnetize. They are

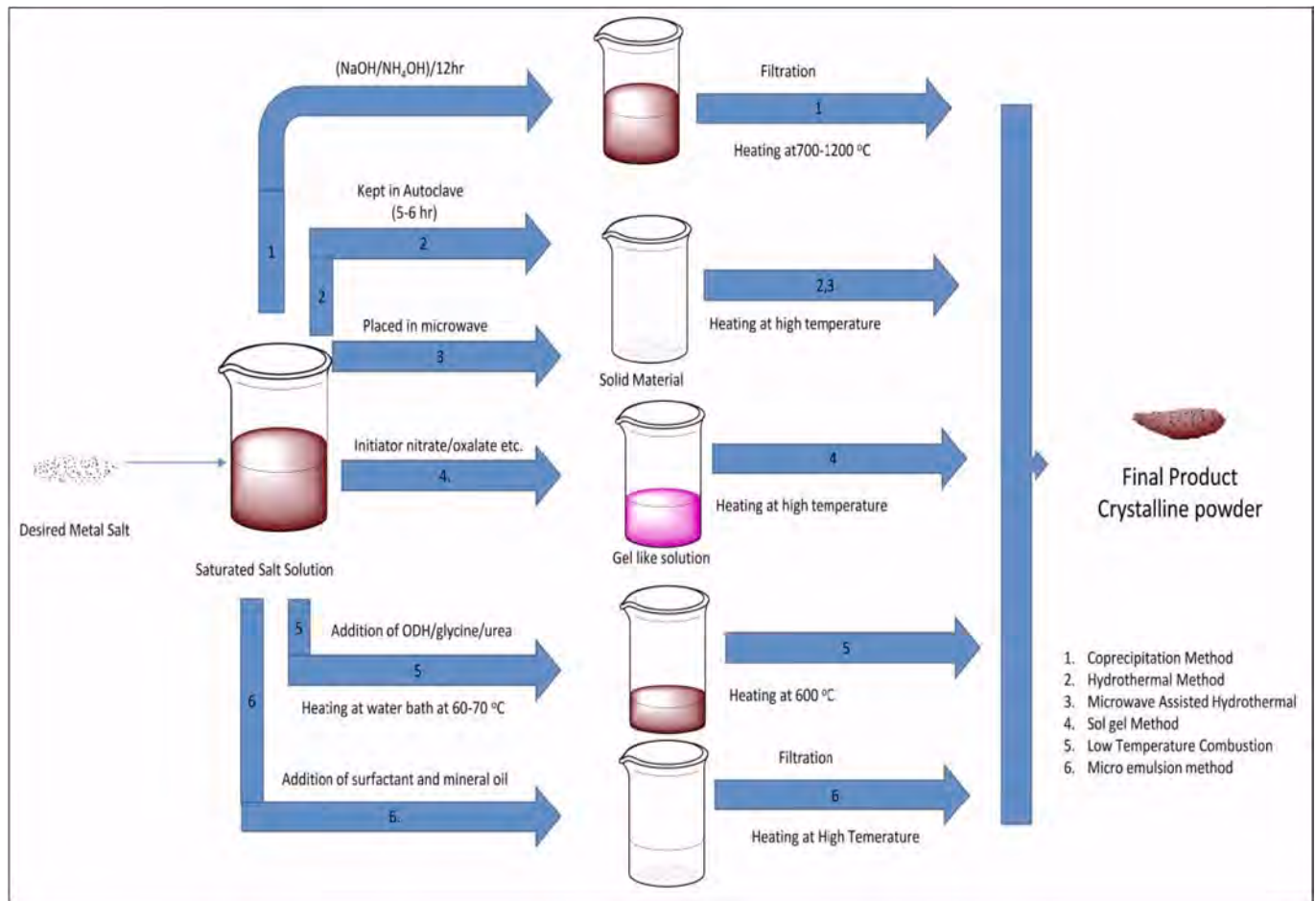


Fig 2. Graphical design of different manufacturing methods leading to nano ferrites.

used to fabricate permanent magnets for applications such as loudspeakers and small electric motors [38–40]. Soft ferrites have low distinguished coercivity (H_c), so they facilitate change their magnetization and work as conductors of magnetic fields. They are used to fabricate efficient magnetic cores [41–44]. Ferrites are classified by names of common minerals that have the crystal construction to the:

3.1. Spinel ferrite

This is ordinarily given by the general formula $Q(Fe_2O_4)$, where tetrahedral and octahedral interstitial positions are determined with Q (divalent mineral ions such as zinc, cobalt, nickel, manganese) and iron, respectively. Given their usability in the microwave domain, spinel alloys can be utilized as MAMs, since these ferrites have low-conductivity (semiconductor particular) and high magnetic losses. But, spinel ferrites in microwave absorption uses are limited by the low resonance frequency [45,46].

3.2. Garnet ferrite

This is ordinarily given by the general formula $Re_3Fe_5O_{12}$ where Re refers to a trivalent ion for example gadolinium, dysprosium, and neodymium. This kind of ferrites has a comparable structure to the spinel ferrites however with some additional positions (dihedral axis). Garnet is a soft ferrite that has low H_c , and a large M_s . Furthermore, garnet has good chemical stability and the ability to repress EMI [47].

3.3. Hexagonal ferrite

This kind of ferrites has an elevated crystalline magnetic contrast field and flat contrast that enhances their normal resonance in the upper GHz band. This hexagonal ferrite property raises its versatility in a diversity of uses. This ferrite crystallizes into a hexagonal structure. Aside from spinel ferrites, the magnetic structure of these ferrites enables the trait to operate in the entire gigahertz band because of their high essential magnetic variance [48]. There are six kinds of hexagonal ferrites:

3.3.1. M-kind

M-kind ferrites are presented through the general formula $Q(Fe_{12}O_{19})$ where Q stands for mineral ions such as lead, barium, strontium, etc. The contrast of big magnetic crystal properties, cheap cost, elevated curie temperature (T_c), and particular M_s characteristics of these types of ferrites make them efficient microwave substances.

3.3.2. Y-kind

Y-kind ferrites are presented through the formula $T_2Q_2(Fe_{12}O_{22})$ where T stands for mineral ions such as lead, barium, strontium, and the same for the Q such as copper, zinc, cobalt, etc. This kind of ferrites is ferromagnetic substances. Hence, the addition of mineral ions in these hexaferrites will lead to dominant their magnetic properties with a view to getting the best microwave absorption [49].

3.3.3. W-kind

W-kind ferrites are obtained with the formula $T_2Q_2(Fe_{16}O_{27})$. The structures of these ferrites are linked to the M-kind. These ferrites

Table 1

Summary of the features and limitations of the main synthesis techniques.

Technique	Nanomaterial	Calcination temperature (°F)	Size (nm)	Features	Limitations	Refs.
Hydrothermal	Mn _{1-x} Zn _x Fe ₂ O ₄	338	15	Controlled size. High yield. Scalable.	Previous information on solubility is wanted. High pressure.	[73]
Mechano-Thermal	ZnFe ₂ O ₄	248	9–20	Fine particle size.	Time-consuming.	[74]
	MgFe ₂ O ₄	752–1292	5–8	Accumulation of ferric oxide.	Existence of impurities.	[75]
	ZnFe ₂ O ₄	752–1022	3–20		Poor yield.	[76]
Microwave –Thermal	BiFeO ₃	356	130	Rapid operation.	Exaggerated growth existence of impurities.	[77]
	BiFeO ₃	752–1112	20–160	Cost-effective.		[78]
	CoFe ₂ O ₄	1112–1472	11–12	They obtained a crystalline structure.		[79]
Combustion	Zn _{1-x} Co _x Fe ₂ O ₄	1742	30–40	Cost-effective process.	Opportunity for impurity forming.	[80]
	CdFe ₂ O ₄	1742	12–27	Low-temperature wanted.	High temperature is wanted.	[81]
	MgFe ₂ O ₄	932	12–25	Potentially of multi-component.		[82]
	BaNi ₂ Fe ₁₆ O ₂₇	1292–1832	10–70	Nanoparticle forming.		[83]
Sol-Gel	Sm _{1-x} Ca _x FeO _{3-y}	1292–1832	100	Controlled size and form.	Expensive process.	[84]
	Sr _{0.7} Nd _{0.3} Fe _x Co _{0.3} O ₁₉	2012	40–50	Better homogeneity.	Requests complete monitoring.	[85]
	Mn _{1-x} Zn _x Fe ₂ O ₄	1292–2012	500	Low cost.		[86]
	NiFe ₂ O ₄	842	11–16			[87]
Co-precipitation	NiFe ₂ O ₄	*	>50	Decrease in the reaction temperature.	The solubility of interactivity materials impacts the precipitation ratio.	[63]
	Mg _{0.5} Ni _{0.5} Fe ₂ O ₄		290–340			[64]
	CoCr _x Fe _{2-x} O ₄		15–23	Aqueous media.	Poor crystallinity.	[65]
	NiFe ₂ O ₄		8–20	Symmetric sized.	Time-consuming.	[66]
Micro Emulsion	CoFe ₂ O ₄	1112	28	Nanoparticle forming.	Temperature-dependent.	[67]
	SrFe ₁₂ O ₁₉	752–1832	60	Single-phase nano-particles.	Existence of impurities.	[88]
	Ni _{0.5} Zn _{0.5} Fe ₂ O ₄	1112	50	Regular crystalline structure.	Less yield.	[89]
Wet chemical	BiFeO ₃	842–1202	50–200	Cost-effective.	Poor yield.	[68]
	Mg _{1-x} Zn _x Fe ₂ O ₄	752–1652	100–150	Low-temperature wanted.	Possible impurity. Contamination.	[69]
	MnFe ₂ O ₄	1292–2192	14–40	Fine particle size.		[70]
Refluxing	Ni _x Zn _{1-x} Fe ₂ O ₄	212	14–19	Control on reaction rate. Symmetric size of particles.	Low yield. Time-consuming.	[72]

properties relied on the particle shape and the way of composition and arrangement of cations in the crystal body [50,51].

3.3.4. X-kind

X-kind ferrites are obtained with the formula T₂Q₂-(Fe₂₈O₄₆) [52]. X-kind hexaferrites can be thought of as a blend of M and W-kind hexaferrites. Compared with M and W-kind hexaferrites, these ferrites possess bigger T_c and M_s, thus they act as the best MAMs.

3.3.5. Z-kind

Z-kind ferrites are presented through the formula T₃Q₂-(Fe₁₄O₄₁). These hexaferrites have a perfect permeability and more elevated resonant frequency (f_r) compared to spinel ferrites. This is a reason why these ferrites are only utilized in microwave systems such as antennas, inductors and permanent magnetic applications [53].

3.3.6. U-kind

The U-kind hexaferrites are obtained with the formula T₄Q₂-(Fe₃₆O₆₀). Among the hexaferrites, these ferrites have greater thermal stability, and high M_s [48]. Hence, this kind of ferrites has been utilized in a lot of research on Electromagnetic interference uses.

4. Synthesis techniques of nano ferrites

The way of synthesis is of most important to get the desired output as characteristics of different kinds of nano ferrites changes significantly with various techniques of synthesis. For example, the size and form of particles define the characteristics of nano ferrites, which in the turn are organized by way of synthesis. Nano ferrites can be manufactured via various techniques as shown in Fig. 2.

4.1. Thermal technique

An ideal thermal technique includes a chain of various steps for getting nano ferrites and their composites. These methodologies of synthesis involve hydrothermal, microwave-aided hydrothermal (MAH), colloid mill or mechano-hydrothermal, combustion, and thermal decomposition method techniques. Nano-particles acquired from the thermal process on the decay of organometallic precursors usually submit symmetric shape and size dispensation. Chemical reactions occur in the hydrothermal method of initial materials (mineral salts) within an aqueous medium under certain conditions of temperature and pressure. The preparation process takes place in special reactors through which the interaction conditions can be controlled to crystallize the ferrite material directly from the solution [54–57]. Some researchers have modified this method by linking it to microwaves treatment to obtain products with unique characteristics such as grain size and microscopic shape [58]. Table 1 shows the features and limitations of the thermal technique.

4.2. Sol-Gel technique

The sol-gel technique can be defined as forming a relatively stable solid phase at a specific temperature starting from the liquid phase. The main reactions in this method are the hydrolysis phase, where the acids and bases are used as catalysts, and the condensation phase. In this phase, the molecules resulting from hydrolysis are linked together to form a three-dimensional structure. The essential primary materials used in this technique are chlorides and nitrates of metals [59–61]. On the other hand, it is necessary to carefully control the variables of the sol-gel method to obtain a homogeneous final product and good magnetic and microwave absorption properties, the most important of which are: purity, quality of raw materials, reaction temperature, stirring quality (mechanical, ultrasound, and magnetism), and finally the pH

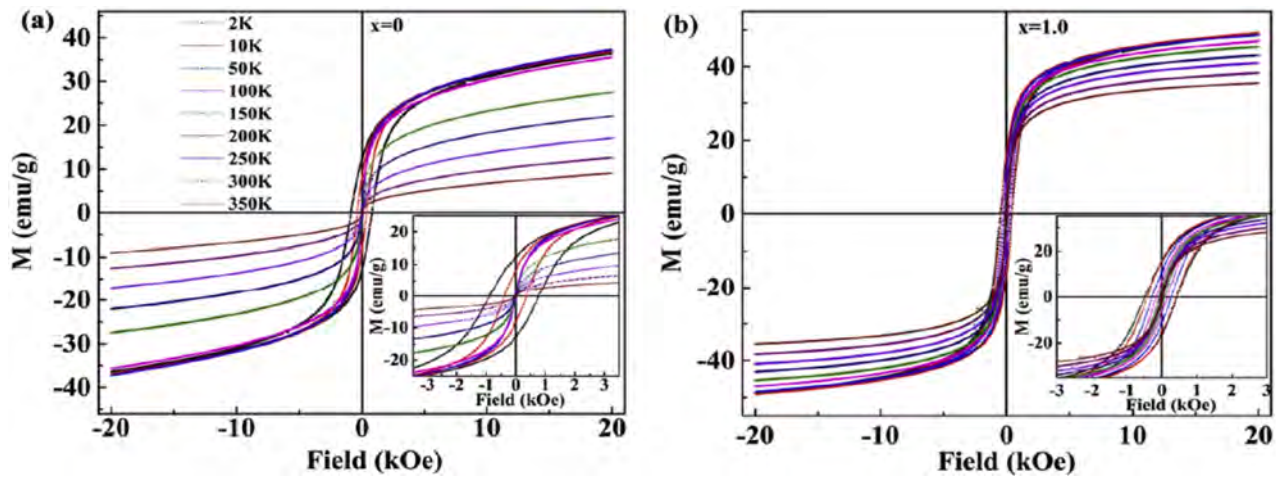


Fig 3. (a, b) Hysteresis loops have measured at various temperatures for $x = 0$ and $x = 1$ compositions.

value. Mallesh et al. prepared $\text{Mn}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0-1$) by sol-gel technique. The microstructure and low-temperature magnetic characteristics of ferrite nanoparticles were examined. The results showed the average particle size between 13 and 20 nm. As for the temperature and magnetic field reliance the results of magnetization, a super-paramagnetic (SPM)-like conduct is shown with a big magnetic moment ($\sim 104 \mu_B$) in particles [62]. The hysteresis loops have obtained at various temperatures for $x = 0$ and $x = 1$ compositions as shown in Fig. 3. Table 1 shows the advantages and disadvantages of the sol-gel technique.

4.3. Co-precipitation technique

This technique is considered one of the most important to prepare ferrite nanomaterials. It mainly depends on preparing an aqueous solution based on suitable initial materials to form the ferrite, adding a convenient sedimentation factor until a convenient pH is reached, and a precipitate is obtained, followed by a filtration and drying process, and heat treatment to obtain the nano ferrite powder. Among the most significant initial materials used in this method: metal chlorides, metal nitrate, metal sulfate as sources of mineral cations, ammonium hydroxide, and sodium hydroxide as sedimentation agents [63–66]. Table 1 shows a summary of the features and limitations of the co-precipitation technique.

4.4. Microemulsion technique

The microemulsion technique is used for attaining more concern in essential as well as manufacturing research due to their unique characteristics. We mention some of them like thermodynamic stability, sizeable interfacial area, and capability to get dissolvable in immiscible liquids. The microemulsion technique includes three segments, water, oil, and surfactant. During blending organometal antecedents, a precipitate is formed. This technique controls different particle characteristics like homogeneity, geometry, morphology, and particle size. These particles are used in magnetic recording and microelectronic devices [67]. Table 1 shows the advantages and disadvantages of the microemulsion technique.

4.5. Other techniques

These kinds of techniques, like the refluxing technique, ceramic technique, wet chemical technique, etc. [68–72]. The selection of suitable synthetic techniques is of immense significance for the manufacture of nano ferrites and is collected in Table 1.

5. Parameters affecting properties of nano ferrites:

The variation in nano ferrites characteristics can be tuned by controlling the different parameters of synthesis, like the composition,

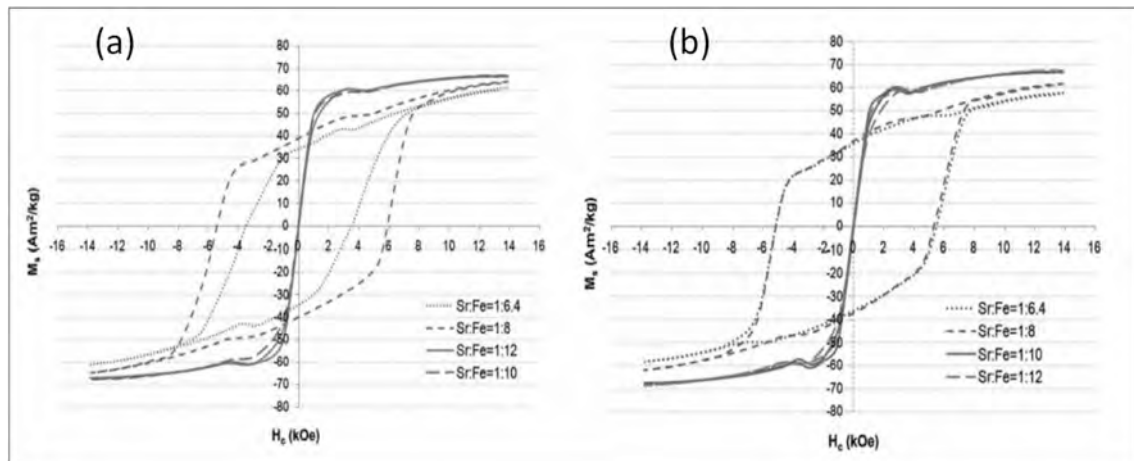


Fig 4. The hysteresis curves of $\text{SrFe}_{12}\text{O}_{19}$ manufactured by the co-precipitation technique (a) and the microemulsion technique (b) with various $\text{Sr}^{2+}/\text{Fe}^{3+}$ mole percentage and calcined at 900°C .

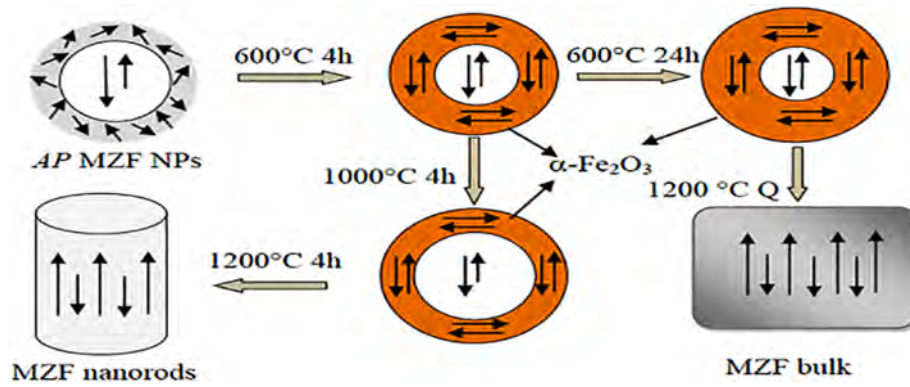


Fig 5. Phenomenological model of phase development in MZF NPs.

combustion temperature, and value of pH.

5.1. Composition

The composition of interacting materials is a significant factor for controlling the nano ferrites by changing the mole percentage of the interacting substances. Drofenik et al. prepared $\text{SrFe}_{12}\text{O}_{19}$ by the co-precipitation technique. The results referred that the reduction in the $\text{Sr}^{2+}/\text{Fe}^{3+}$ mole percentage from 1:8 included a severe alter in magnetic conduct that appeared by an extreme variation in the hysteresis loop as shown in Fig. 4 [88].

5.2. Combustion temperature

Combustion or annealing temperature is the essential parameter that impacts the magnetic, microwave absorbing properties, and

morphological nature of nanoparticles [90–93]. Malleesh et al. prepared $\text{Mn}_x\text{Zn}_{1-x}\text{Fe}_2\text{O}_4$ ($0 \leq x \leq 1.0$) compositions by sol-gel method. The structure, thermal stability, and magnetic characteristics of as-prepared and annealed patterns have been studied. Though, as-prepared and 1200 °C air annealed patterns show cubic spinel ferrite phase, they crumble into $\alpha\text{-Fe}_2\text{O}_3$, or/and $\alpha\text{-Mn}_2\text{O}_3$ phases along with the poor quality of ferrite phase on annealing at 600 °C in the air. Fig. 5 shows the phenomenological model of phase development in MZF NPs. Present investigations show that the stability of spinel ferrite phase is sensitive to (i) Mn concentration (ii) the annealing temperature and (iii) environments (air, Oxygen, and Argon atmosphere) in which annealing experiments were executed [94]. Prabu et al. prepared the MgFe_2O_4 by sol-gel method and studied the structure and magnetic characteristics of Magnesium ferrite, The XRD samples of as studied and annealed nanoparticles of MgFe_2O_4 patterns showed pure spinel phase. But annealing at intermediate temperature (500 °C–1000 °C) outcomes in the

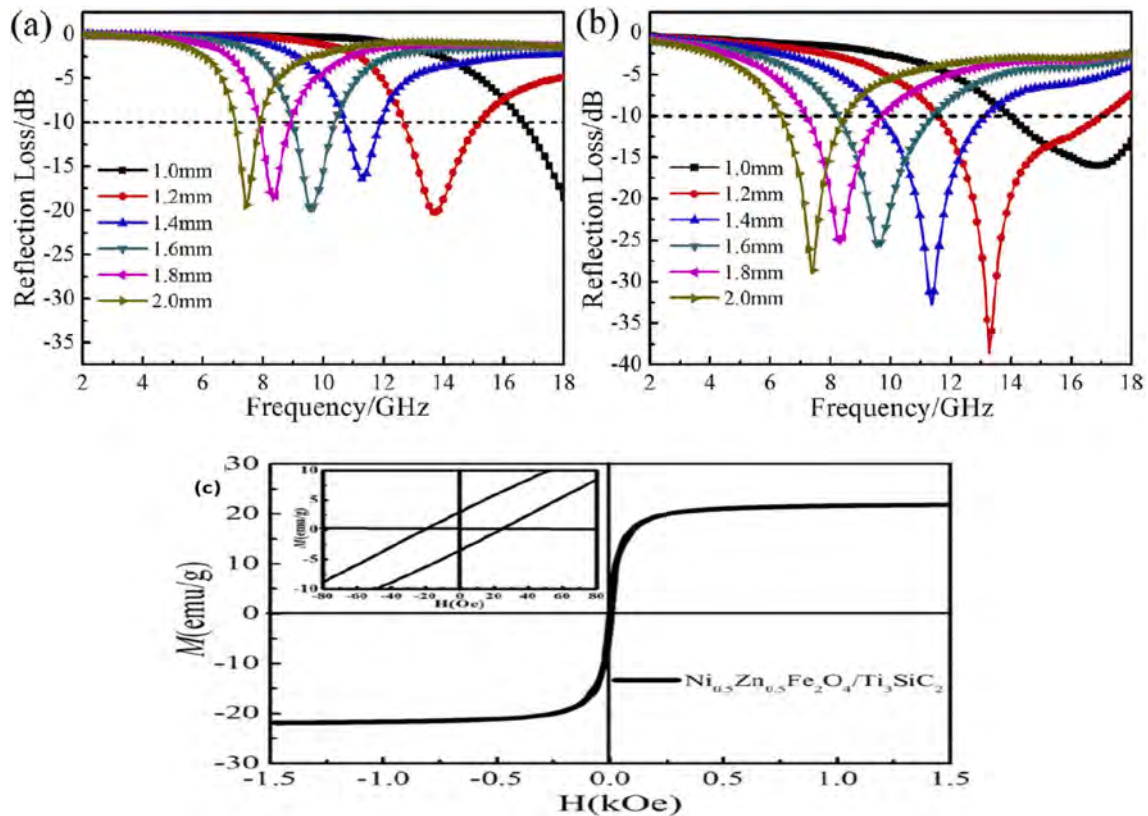


Fig 6. Measured RL of (a) Ti_3SiC_2 , (b) $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4/\text{Ti}_3\text{SiC}_2$ absorbing coating with different thicknesses and (c) Hysteresis loop of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4/\text{Ti}_3\text{SiC}_2$ pattern, inset shows enlarged region of the loop around the origin.

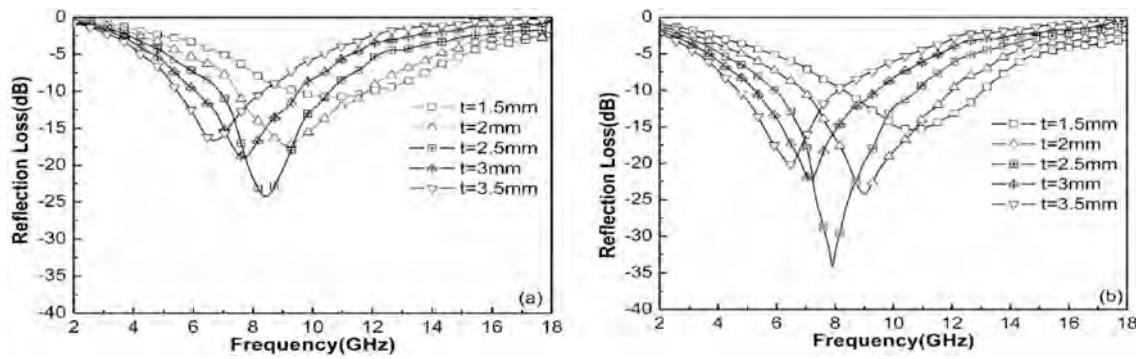


Fig 7. Frequency dependence of reflection loss of $\text{Ni}_{0.7}\text{Zn}_{0.3}\text{Y}_x\text{Fe}_{2-x}\text{O}_4$ ferrite ($x = 0$, (a); $x = 0.2$, (b)) at various thicknesses.

development of $\alpha\text{-Fe}_2\text{O}_3$, MgO secondary phases along with ferrite phase. This leads to the deterioration of magnetic characteristics [95].

5.3. Value of pH

The variance in pH value controls the microwave absorbing characteristics and morphologies of nanomaterials. Where the nano ferrites are immediately impacted by the pH value [96]. Huang et al. studied the Co-Zn ferrite by the co-precipitation technique at various pH situations in the field of 9–11. The results detected when the pH situation was raised from 9 to 11, the particle size for the compound reduced from 40 nm to 30 nm, the difference in microstructure considers a significant factor in dominating the EM characteristics. The magnetic loss was 0.2–0.5, and the dielectric loss was 0.02–0.07 for the compound at pH of 9, which shows significantly improved magnetic loss and dielectric loss characteristics than the patterns studied at pH of 10 and 11 [97].

6. Microwave absorbent of ferrite materials

The researchers worked to develop the absorption materials of the microwave by studying several factors and variables such as the method of preparation, the type of ferrite material, the effect of the process of substitution with different mineral cations, the thickness of the absorbent substances, etc. Luo et al. prepared the Ti_3SiC_2 particles encapsulated by $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ shell through the sol-gel technique, which provides the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4/\text{Ti}_3\text{SiC}_2$ compound owning a good permittivity and coveted bigger permeability, consequencing is a better impedance matching characteristics and effective EM attenuation ability, as shown in (Fig. 6: a–b), the measured absorbing bandwidth under -10 dB was 5.3 GHz and maximum RL of -38.6 dB were obtained for the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4/\text{Ti}_3\text{SiC}_2$ absorbing coating with a thickness of 1.2 mm. The hysteresis loop of the $\text{Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4/\text{Ti}_3\text{SiC}_2$ pattern was measured and the results were M_s and H_c were 21.82 emu/g and 33.07 Oe, respectively as shown in Fig. 6(c) [98].

Mingyuan et al. studied $\text{Ni}_{0.7}\text{Zn}_{0.3}\text{Fe}_2\text{O}_4$ and $\text{Ni}_{0.7}\text{Zn}_{0.3}\text{Y}_x\text{Fe}_{2-x}\text{O}_4$ by the sol-gel method. The absorption results show when the material is thicker, that leads the matching frequency will displace towards the lower frequencies, as shown in (Fig. 7: a–b) [99]. We can be explained that the spreading wavelength in the absorbent material λ_a is given by the following relationship (11) [100–102]:

$$\lambda_a = \frac{c}{f \sqrt{|\mu_r| |\epsilon_r|}} \quad (11)$$

When the thickness of the absorbent material is equivalent to a fourth of the spreading wavelength in the absorbent material, then the reflected wave from the surface separating the two mediums (absorbent material-air) will interfere with the phase-varying wave and reflected from the surface separating the two mediums (metal-absorbent material). This thickness is called the matching thickness, and it is given by the following relationship (12) [103–105].

$$t_m = \frac{n\lambda_a}{4} = \frac{nc}{4f \sqrt{|\mu_r| |\epsilon_r|}} \quad (n = 1, 3, 5, \dots) \quad (12)$$

Bueno et al. prepared $\text{Cu}_{0.2}\text{Ni}_{0.4}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4$ by Citrate precursor and studied the microwave absorption properties for this ferrite. The results indicated this ferrite exceeded the -10 dB threshold within the range (X-band) on a range reached to 2.4 GHz [106]. Ghosh et al. studied the same previous compound but prepared it in a different method, which was the co-sedimentation method. The results indicated this ferrite exceeded the -10 dB threshold within the range (X-band) on a range reached to 4.1 GHz with a thickness of 2.5 mm and the loading percentage 30%w/w [107]. Where the changes in microwave absorption properties were noticed with the change of the preparation method. Chen et al. prepared the spinel ferrite, which was $\text{Ni}_x\text{Co}_{1-x}\text{Fe}_2\text{O}_4$ ($x = 0.5, 0.8$) by ball milling. The results illustrated for $\text{Ni}_{0.8}\text{Co}_{0.2}\text{Fe}_2\text{O}_4$ that the maximum RL was -35.5 dB at the frequency of 11.5 GHz for the thickness of 2.5 mm, the absorption bandwidth under -10 dB was 3.2 GHz, the dielectric loss was ($\epsilon_r = 9.6 + i0.13$), and the magnetic loss was ($\mu_r = 1 - i0.3$). As for $\text{Ni}_{0.5}\text{Co}_{0.5}\text{Fe}_2\text{O}_4$ that the RL was -30.6 dB at the frequency of 11.9 GHz for the thickness of 2.5 mm, the absorption bandwidth under -10 dB was 3.4 GHz, the dielectric loss was ($\epsilon_r = 8.3 + i0.25$), and the magnetic loss was ($\mu_r = 0.7 - i0.3$) [108]. Where the changes in microwave absorption properties were observed with the change of the compound composition, as mentioned above.

On the other hand, other researchers have studied the effect of the process of substitution with a number of mineral cations and substitution rates on ferrite. Almessiere et al. prepared $[\text{Ni}_{0.4}\text{Cu}_{0.2}\text{Zn}_{0.4}](\text{Nd}_x\text{Y}_{1-x}\text{Fe}_{2-2x})\text{O}_4$ ($x \leq 0.05$) with partly Nd/Y replaced by citrate sol-gel auto-combustion method. The magnetic proprieties were studied for specimens at temperature 300 K, where the hysteresis loops for the specimens that are non-substituted ($x = 0$) showed superparamagnetic conduct, whereas the specimens which Nd-Y substituted NiCuZn ferrite showed soft ferrimagnetic status. It was noticed that the volume of magnetization decreases with an increase in Nd^{3+} and Y^{3+} amounts. ZFC-FC magnetic measurements detected the presence of dipolar reactions, which illustrate a partly blocked case in conformity with hysteresis loops at temperature 300 K. For all tested $[\text{Ni}_{0.4}\text{Cu}_{0.2}\text{Zn}_{0.4}](\text{Nd}_x\text{Y}_{1-x}\text{Fe}_{2-2x})\text{O}_4$ ($x \leq 0.05$) NSF, the maximum intense absorption was noticed at the frequencies of 2.49–4.15 GHz. The maximum RL -44.69 dB was noticed [109]. Slimani et al. prepared $\text{Ni}_{0.4}\text{Cu}_{0.2}\text{Zn}_{0.4}\text{Tb}_x\text{Fe}_{2-x}\text{O}_4$ ($0.0 \leq x \leq 0.10$) by sonochemical method. The NSF's structure was verified by XRD test. In addition to that, the microstructural was investigated by SEM device. The results showed that the substitutions rate gave a substantial impact on dielectric characteristics, whereas ion substitution has limited however a distinguished impact on AC/DC conductivity variation. Finally, the appearances of the EM absorption in the field of 1.8–3.8 GHz were noticed [110]. Almessiere et al. prepared the partly Eu substituted $\text{Ni}_{0.4}\text{Cu}_{0.2}\text{Zn}_{0.4}\text{Eu}_x\text{Fe}_{2-x}\text{O}_4$ ($0.0 \leq x \leq 0.10$) nanostructured spinel ferrites (NSFs) via sol-gel auto-combustion technique. The XRD analyses confirmed the presence of the single-phase

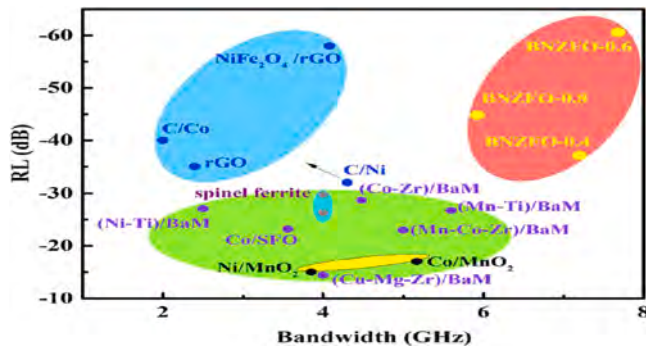


Fig 8. The comparing of the absorption characteristics got in this research with those in other researches.

structure in all the studied patterns. The paramagnetic contribution of the NSF's rose with the increase in Eu^{3+} contents. The frequency dispersals of the permeability and permittivity were used to define the RL in the 1 to 20 GHz frequency field [111]. Slimani et al. studied the dysprosium ions (Dy^{3+})-substituted NFs of compound $[\text{Ni}_{0.5}\text{Co}_{0.5}](\text{Dy}_x\text{Fe}_{2-x})\text{O}_4$ ($x \leq 0.08$) utilizing the citrate gel method. All the NFs referred that the absorption of the EM radiation was in the frequency range 2.9–5.5 GHz because of the ferromagnetic resonance. It's been confirmed that by dominating the Dy^{3+} contents accurately, the MA and magnetic properties of the suggested spinel NFs can be designed [112]. From these studies were observed that the non-substituted ferrites were

distinguished by their modest ability to absorb microwaves, which necessitated the search for the effect of the process of substitution with a number of mineral cations and substitution rates on ferrite through which the microwave absorption and magnetic properties were improved, as the tests result indicated.

On the other hand, other researchers have studied the effect of Doped on microwave absorption properties. Bai et al. studied the Ni^{2+} - Zr^{4+} Co Doped barium ferrite ceramics, the results showed that $\text{BNZFO}_{0.4}$ and $\text{BNZFO}_{0.6}$ have bigger attenuation constant than the others, indicating better MA or attenuation. The comparing of the MA characteristics got in this research with those in other researches is shown in Fig. 8. It refers that the RL and efficient absorption bandwidth under -10 dB of this research are exceeding other researches. The high MA characteristic of this absorbing is referred to as its essential double normal resonance in microscale [113]. As well, the addition of 8th collection materials in SiCN ceramics [114–118], and other materials in SiC ceramics [119–121] can also promote the MA performance of absorbing to a big range.

These studies were shown the great effect of the change of method of preparation, the type of ferrite material, the effect of the process of substitution with different mineral cations, the thickness of the absorbent substances, and Doped on the microwave absorption properties. The microwave absorbing behavior of ferrite materials is shown in Table 2.

Table 2
Microwave absorbing behavior of ferrites and their composites.

Nanomaterial	T (mm)	Freq (GHz)	Max RL (dB)	(B.W.) _{-10 dB} (GHz)	ϵ'_{max}	ϵ''_{max}	μ'_{max}	μ''_{max}	Refs.
Fe_3O_4 30 wt%	4.0	5.4	-26.9	3.1	9.3	0.3	1.2	0.52	[147]
Fe_3O_4 30 wt%	3.0	8.2	-21.1	2.7	9.5	0.4	0.9	0.38	
Fe_3O_4 40 wt%	3.0	6.9	-23.3	3.1	11.1	1.6	1.06	0.45	[148]
Fe_3O_4 40 wt%	3.5	5.5	-27.8	2.6	11.0	1.4	1.23	0.54	
Fe_3O_4 40 wt%	4.0	4.7	-44.7	2.1	11.0	1.3	1.30	0.58	
Fe_3O_4 nanowires	2.5	8.3	-16.7	2.7	6.2	0.2	0.98	0.20	[149]
Fe_3O_4 nanosheets	2.5	10.2	-8.89	0.0	8.1 2	2.1	0.90	0.01	
Fe_3O_4 90%	1.0	14.1	-42.3	4.3	23.6	2.9	0.3	0.3	[150]
Fe_3O_4 80%	1.3	15.1	-33.7	3.2	17.7	3.9	0.5	0.06	
Fe_3O_4 70%	5.0	3.4	-34.9	1.5	12.1	1.2	1.2	0.6	
$\text{Ni:B/Fe}_3\text{O}_4$	6.0	5.4	-28.4	2.6	6.6	1.0	0.8	0.3	[151]
$(\text{Ni}_{0.5}\text{Zn}_{0.5})\text{Fe}_2\text{O}_4$	2.97	11.9	-36.2	5.2	7.5	0.05	0.5	0.2	[152]
$(\text{Ni}_{0.4}\text{Cu}_{0.2}\text{Zn}_{0.4})\text{Fe}_2\text{O}_4$	9.2	1.1	-35.6	1.6	8.1	-0.01	2.1	3.8	
	4.2	4.1	-48.1	3.6	7.05	0.03	1.56	1.49	
MnFe_2O_4	2.0	9.4	-42.5	0.3	1.5	0.35	4.7	0.73	[153]
$\text{Co}_{0.5}\text{Mn}_{0.5}\text{Fe}_2\text{O}_4$	2.0	10.5	-47.0	1.0	3.8	0.36	7.1	1.02	
CoFe_2O_4	2.0	10.7	-39.8	1.0	7.5	0.46	8.9	1.42	
$\text{Bi}_{0.8}\text{La}_{0.2}\text{FeO}_3$	6.0	11.5	-29.7	1.1	9.8	1.4	1.0	0.9	[154]
$\text{PANI/Li}_{0.35}\text{Zn}_{0.3}\text{Fe}_{2.35}\text{O}_4$	2.0	14.6	-37.5	2.0	8.2	5.0	1.04	0.1	[155]
$\text{Ni}_{0.6}\text{Zn}_{0.4}\text{Fe}_2\text{O}_4/\text{PANI}$	2.6	12.8	-41.0	5.0	6.2	6.0	0.97	-0.05	[156]
$\text{C/Fe}_3\text{O}_4$	1.9	12.1	-52.8	2.5	12.0	1.5	0.94	0.10	[157]
$\text{C/Fe}_3\text{O}_4$ NR δ (0.5)	6.2	3.4	-55.7	2.9	11.5	2.7	1.35	0.54	[158]
$\text{C/Fe}_3\text{O}_4$ NR δ (1)	4.5	6.0	-55.1	2.8	10.6	2.5	0.88	0.26	
$\text{C/Fe}_3\text{O}_4$ NR δ (2)	4.2	6.1	-51.8	2.7	9.3	1.7	0.93	0.93	
$\text{C/Fe}_3\text{O}_4$ NR δ (4)	1.9	13.8	-55.3	3.8	6.7	1.6	0.95	-0.06	
$\text{ZnO/Fe}_3\text{O}_4$	5.0	1.66	-12.92	0.85	3.4	1.23	2.4	4.0	[159]
$\text{Fe:Mn/Fe}_3\text{O}_4$	1.85	13.9	-27.7	4.2	8.9	2.5	1.0	1.0	[160]
$(\text{MnNi})_{0.2}\text{Co}_{0.6}\text{BaTiFe}_{10}\text{O}_{19}$	1.8	13.5	-53.0	5.4	6.7	0.4	0.8	0.7	[161]
$(\text{MnNi})_{0.25}\text{Co}_{0.5}\text{BaTiFe}_{10}\text{O}_{19}$	1.8	14.1	-68.9	4.9	6.5	0.4	1.2	0.7	
$\text{ZnO/BaFe}_{12}\text{O}_{19}$	6.8	16.0	-37.3	3.0	3.1	1.3	0.7	0.03	[162]
$\text{BaCe}_{0.05}\text{Fe}_{11.95}\text{O}_{19}$	3.5	12.8	-37.4	8.1	2.72	1.38	1.10	0.38	[163]
	5.0	11.3	-31.5	3.5	1.6	1.6	1.4	0.77	
$\text{ZnFe}_2\text{O}_4/\text{rGO}$	2.5	9.3	-41.1	2.6	11.6	3.7	0.94	0.07	[164]
$\text{NiFe}_2\text{O}_4/\text{rGO}$	3.0	9.2	-39.6	3.0	8.0	3.0	1.0	0.1	[165]
	1.9	14.5	-36.9	5.2	9.0	1.6	0.78	0.2	
$\text{CoFe}_2\text{O}_4/\text{rGO}$	1.6	14.7	-44.1	4.5	9.4	9.3	0.98	0.5	[166]
$\text{NiFe}_2\text{O}_4/\text{grapheme/ polyaniline}$	2.5	12.5	-50.5	5.3	6.3	1.9	0.96	0.02	[167]
	3.0	10.0	-32.4	3.5	6.6	2.8	1.1	0.11	
$\text{MWCNT/Ni}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$	2	10.40	-10.03	0.08	18.5	8.5	0.98	0.03	[168]
	3	8.46	-19.34	1.24	11.7	4.2	0.94	0.01	
$\text{CF/Fe}_3\text{O}_4/\text{BN}$	3.0	12.5	-14.0	4.2	3.1	0.4	1.0	0.01	[169]

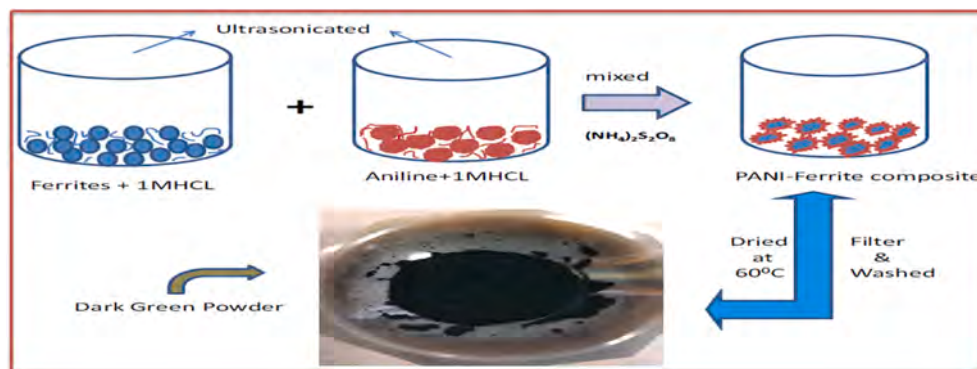


Fig 9. Polymerization technique of PANI-ferrite nanocomposite.

7. Microwave absorbent of ferrite/polymer composites:

The researchers attempted to improve the microwave absorption width by preparing composite materials with a microscopic structure (core/shell). The outer shell is formed from conductive polymers, while the inner core often is formed from ferrite material (spinel ferrite or hexagonal ferrite) [122,123]. Peng et al. prepared an absorbent composite material consisting of ferrite $\text{Ni}_{0.5x}\text{Zn}_{0.5x}\text{Co}_{2x}\text{Fe}_2\text{O}_4$ ($x = 0-0.5$) and thermoplastic polyurethane (TPU), with a Loading percentage of 80 wt% ferrite, where the highest absorption intensity was -20 dB at the frequency 5.14 GHz for the thickness of 5 mm, and the absorption bandwidth under -10 dB was 0.75 GHz [124]. Bhattacharyya et al. Prepared an absorbing nanocomposite by mixing the $\text{Mg}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$

with thermoplastic polyurethane at the frequency range ($4-15$ GHz), with a Loading percentage of 50 wt% ferrite, then applying the prepared mixture as a coating (thin layer 100 μm). This coating showed wide absorption with RL exceeding 88% of the incoming rays [125]. Furthermore, Singh et al. studied ternary core-shell $\text{Mg}_{0.6}\text{Cu}_{0.4}\text{Fe}_2\text{O}_4$ with PANI matrix nanocomposite by in-situ chemical polymerization technique as shown in Fig. 9, this lightweight nanocomposite displayed the important EM shielding impact of -32.8 dB in the frequency field of X-band [126]. Zhao et al. prepared $\text{PANI}/\text{Co}_{0.5}\text{Zn}_{0.5}\text{Fe}_2\text{O}_4$ by situ polymerization. The results illustrated that the maximum RL was -39.8 dB at the frequency of 22.3 GHz for the thickness of 2 mm, the absorption bandwidth under -10 dB was 10.5 GHz, the dielectric loss was ($\epsilon_r = 19.3- i13.1$), and the magnetic loss was ($\mu_r = 1.7- i0.3$) [127]. Dixit

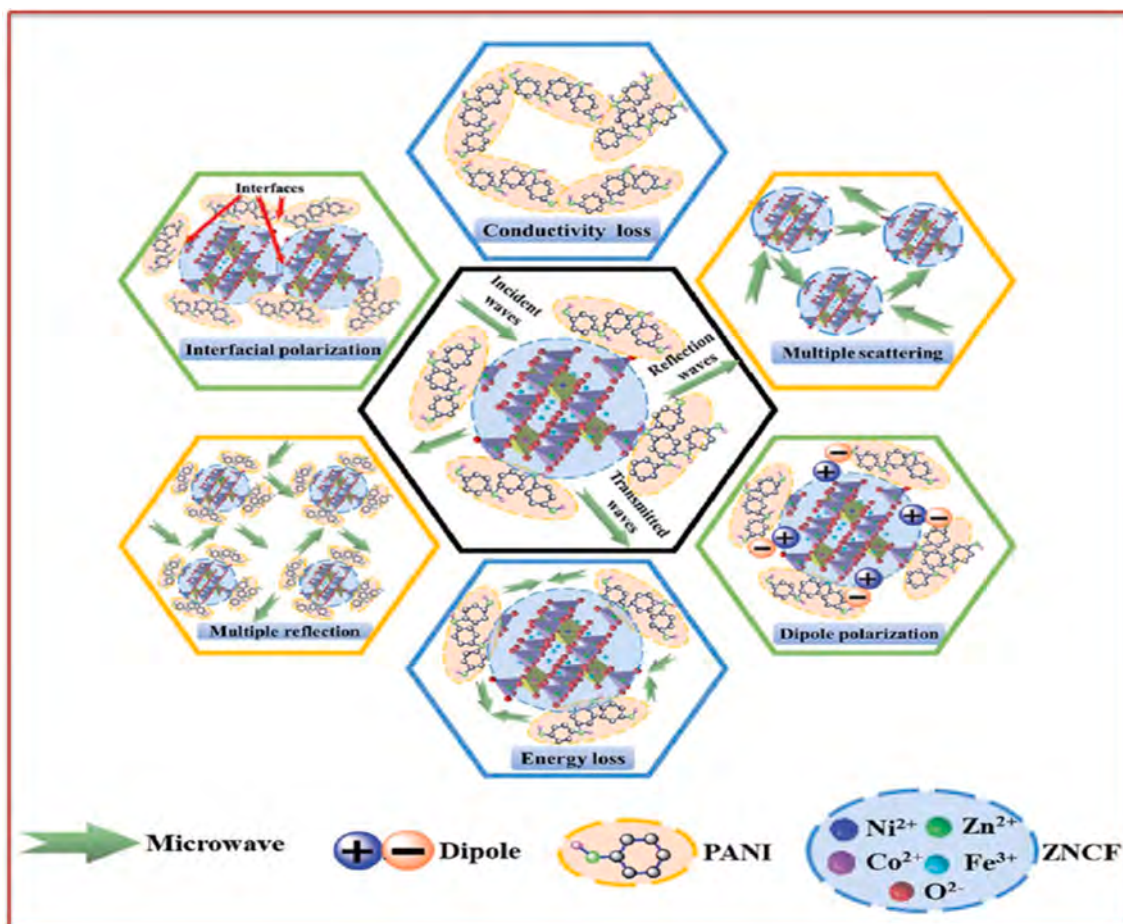


Fig 10. Schematic of MA mechanisms for the PANI/ZNCF compounds.

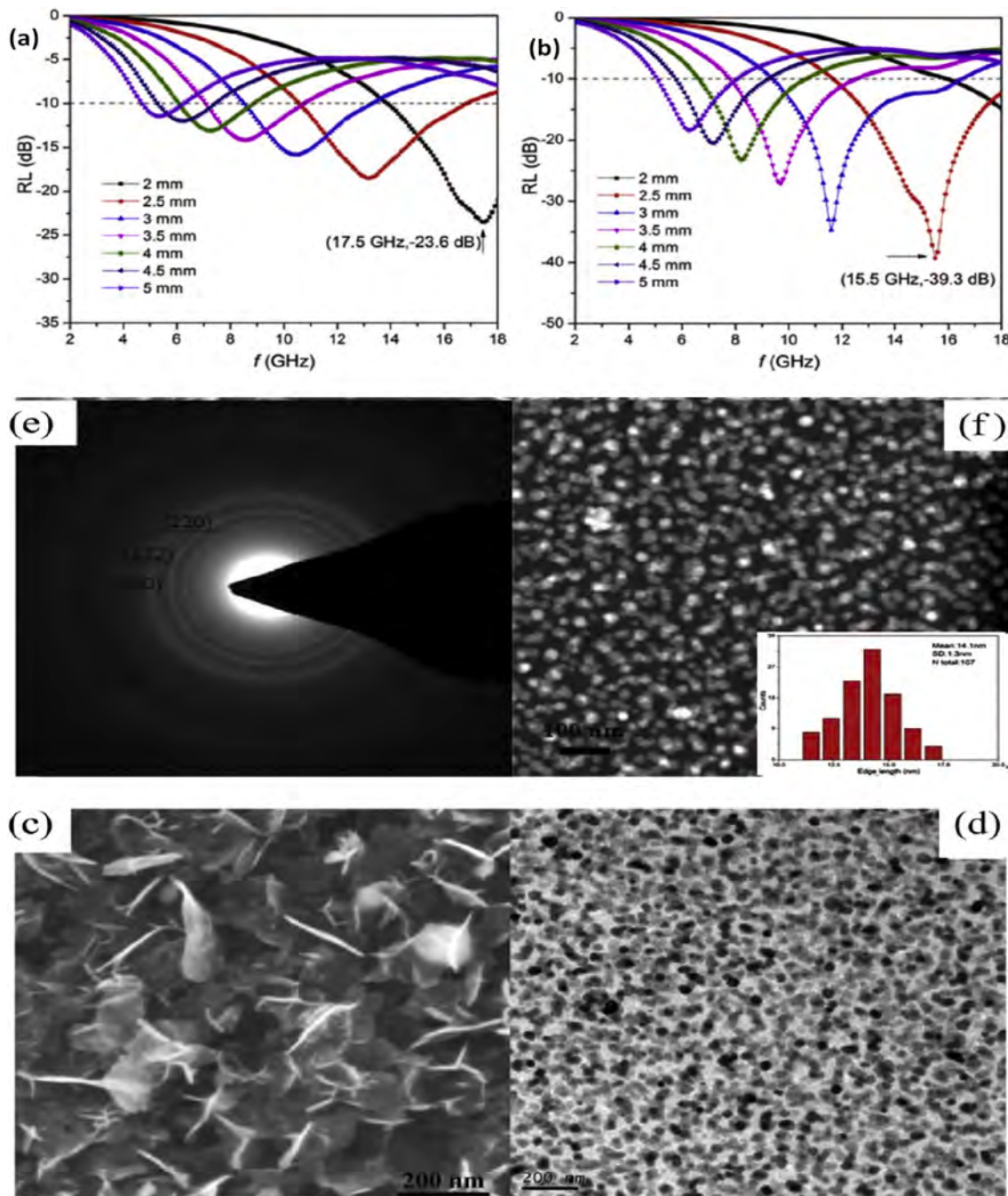


Fig 11. Calculated RL for (a) Amorphous carbon, (b) $\text{Fe}_3\text{O}_4/\text{C}$, and (c) SEM picture, (d) TEM picture, (e) SAED picture, and (f) HAADF picture for $\text{Fe}_3\text{O}_4/\text{C}$ at a 1:1 ratio.

et al. prepared $\text{BaCo}_{0.9}\text{Fe}_{0.05}\text{Si}_{0.95}\text{Fe}_{10.1}\text{O}_{19}$ was dispersed in a polyurethane matrix according to the loading percentages (50, 60, 70, 80%). The composite material with a loading ratio of 80 wt% ferrite showed the highest absorption intensity was -24.5 dB at the frequency of 12 GHz for the thickness of 1.6 mm, and the absorption bandwidth under -10 dB was 2 GHz [128].

On the other hand, other researchers have studied the core/shell/shell on microwave absorption properties. Zhai et al. prepared $\text{Fe}_3\text{O}_4/\text{SiO}_2/\text{PPy}$ (core/shell/shell) via microemulsion polymerization technique. The highest absorption intensity was -40.9 dB at the frequency of 6 GHz for the thickness of 5 mm, and the absorption bandwidth under -10 dB was 6.88 GHz [129]. Weng et al. were able to prepare the composite material $\text{Fe}_3\text{O}_4/\text{polyaniline/Polypyrrole}$ that

exceeded the -10 dB threshold across the entire frequency range (X-band), 5.4 GHz within (Ku-band), and 1.3 GHz within (C-band) for the thickness of 2.6 mm and a loading percentage of 20% w/w. As well, the combination of polymer with ion-doped ferrites is also an efficient approach to get EM absorbers with excellent behavior [130]. Yao et al. explained the systematic impact of interaction circumstances on the characteristics of Co-doped Zn-Ni ferrite/PANI hybrids prepared through interfacial polymerization. The realization outcomes refer that the hybrid gives premium EM absorbing characteristics with maximum RL value of -54.3 dB and efficient absorbing bandwidth under -10 dB was 6.02 GHz for the thickness of 6.8 mm in the optimized polymerization circumstances of 20°C for 12 h. The outstanding EM absorbing characteristics of this PANI/Zn-Ni ferrite hybrid can be illustrated in

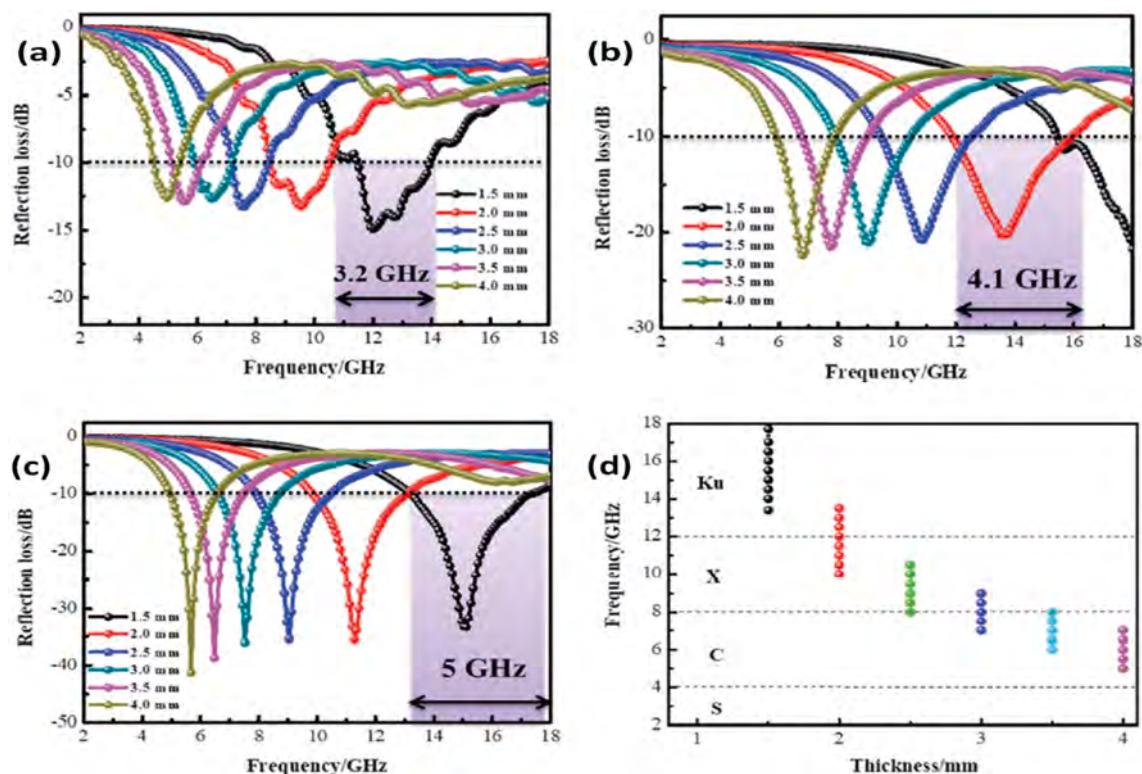


Fig. 12. RL curves of CF (a), CF@CoFe₂O₄ (b) and CF@CoFe₂O₄/MnO₂ composites (c) Efficient absorption bandwidth of CF@CoFe₂O₄/MnO₂ composite at various thicknesses (d).

Fig. 10 for the perfect impedance matching properties, powerful dipole polarization and interfacial polarization impact marked conductivity loss, and multiple dissipation and reflection [131]. On the other hand, in several states, the polymer-based ferrite compounds can be inserted with carbon substances also, e.g. core-shell ferrite/graphene oxide/polyaniline [15], Fe₃O₄@C@PANI [132], cobalt ferrite/graphene/polyaniline [133], and so on. These compounds can own unique EM absorption performance because of the connection absorbing mechanism to present in every part. The review of these researches we were shown illustrates the capacity of these composites to the microwave absorption better compared to ferrite materials and which are characterized by their lightweight and relatively low thickness. The microwave absorbing behavior of ferrite polymer composites is shown in Table 2.

8. Microwave absorbent of ferrite/carbon composites

The nanostructured carbon materials have unique properties, like high conductivity, control of porosity, high mechanical strength, and superb physicochemical characteristics due to their nanoscale size, and the ratio of surface area to volume is quite aloft [134,135]. These prominent structural properties of carbon nanomaterials assist them in reacting with other substances for many new applications, like microwave absorption, and bio, chemical, and mechanical sensors. Many researchers studied the effect of adding different types of carbon (eg, carbon nanotubes (CNTs), carbon fibers (CF), graphene, etc) to ferrite magnetic materials on the microwave absorption that aims to obtain wide absorption bandwidth or reduce both the thickness and the loading percentage. Ahmad et al. prepared a composite material of Ni-Zn ferrite and carbon nanotube through physical mixing. They studied the microwave absorption of the prepared material with a loading percentage of 2.0%_{w/w} for the thickness of 1.0 mm. This material managed to exceed the absorption threshold -10 dB within the two ranges (8.0–12.5 GHz) and (1.0–8.0 GHz) with values of 3.7 GHz and 0.9 GHz, respectively [136]. On the other hand, a number of researchers have

studied the addition of amorphous carbon to Fe₃O₄, for example, Liu et al. prepared amorphous carbon and Fe₃O₄/C, the results for amorphous carbon were showed for RL was -23.6 dB for the thickness of 2 mm at the frequency of 17.5 GHz, the dielectric loss was ($\epsilon_r = 5.1 - i3.2$), and the magnetic loss was ($\mu_r = 1.01 + i0.019$). As for Fe₃O₄/C, the results illustrated RL was -39.3 dB for the thickness of 2.5 mm at the frequency of 15.5 GHz for a 1:1 loading percentage by weight, the dielectric loss was ($\epsilon_r = 4.5 - i2.5$), and the magnetic loss was ($\mu_r = 1.04 + i0.019$). Fig. 11 shows the outcomes were compared between amorphous carbon and Fe₃O₄/C at different thicknesses and implemented some experimental analyses for Fe₃O₄/C at a 1:1 ratio [137]. Besides, a number of researchers have analyzed the effect of carbon concentration on Fe₃O₄, for instance, Wang et al. prepared Fe₃O₄@C (17.84 wt%C), and Fe₃O₄@C (23.41 wt%C) prepared through in-situ polymerization. The results illustrated for Fe₃O₄@C (17.84 wt%C) that the RL was -35.8 dB at the frequency of 4.7 GHz for the thickness of 5 mm, the absorption bandwidth under -10 dB was 1.7 GHz, the dielectric loss was ($\epsilon_r = 9.4 - i2.9$), and the magnetic loss was ($\mu_r = 1.1 - i0.2$). As for Fe₃O₄@C (23.41 wt%C) that the RL was -40.2 dB for the thickness of 1.5 mm at the frequency 15.8 GHz, the absorption bandwidth under -10 dB was 3.9 GHz, the dielectric loss is ($\epsilon_r = 10.2 - i3.7$), and the magnetic loss is ($\mu_r = 1$) [138]. In other cases, a number of researchers have investigated the effect of carbon fiber on ferrite, for instance, Feng et al. prepared CF@CoFe₂O₄ and CF@CoFe₂O₄/MnO₂ composites by the sol-gel technique and hydrothermal interaction. The as-synthesized CF@CoFe₂O₄/MnO₂ composite showed superior MA performance fundamentally because of reasonable EM matching, and its minimum RL value equaled -34 dB with a pattern thickness of 1.5 mm. Fig. 12 shows RL curves of CF (a), CF@CoFe₂O₄ (b) and CF@CoFe₂O₄/MnO₂ composites (c) at a various thicknesses the efficient absorption bandwidth of CF@CoFe₂O₄/MnO₂ composite (d) [139].

On the other hand, a number of researchers have studied the addition of graphene to ferrite, for example, Huang et al. prepared NiFe₂O₄ with garnished graphene (GR) as the substrate for the immediate growth of

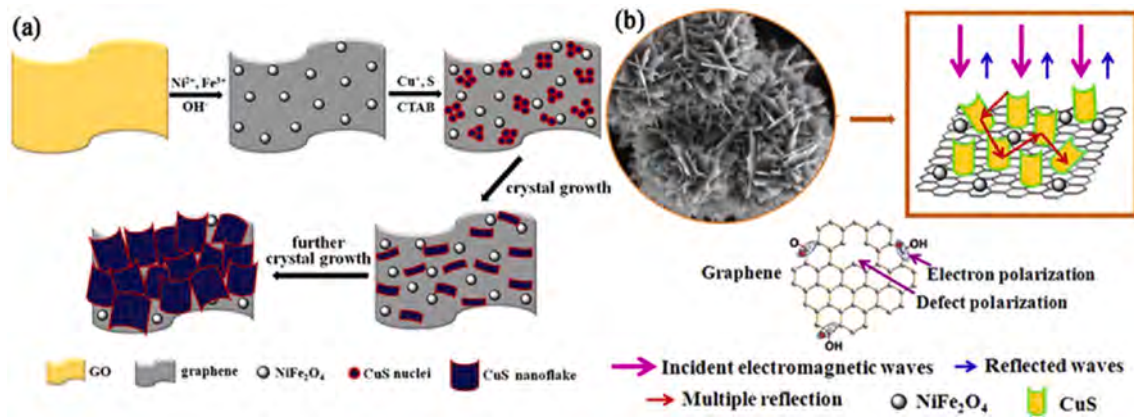


Fig 13. (a) Explanation for the shaping of magnetically garnished GR@CuS. (b) Prospective the mechanism of MA in magnetically garnished GR@CuS.

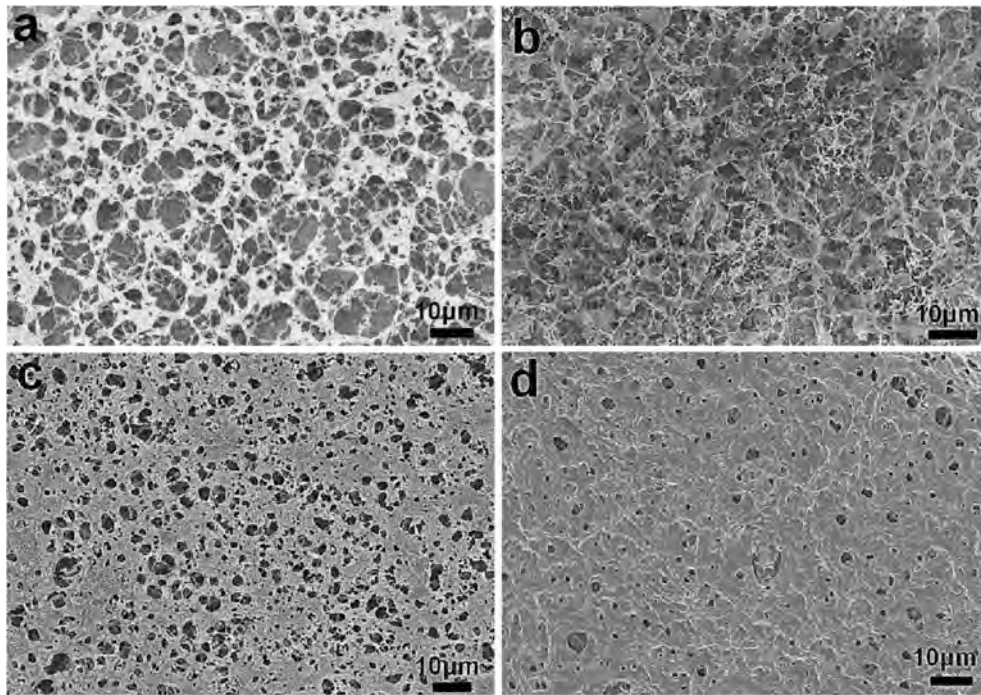


Fig 14. Illustration of the manufactured microstructure of interconnected network made of rGO and CNTs with Fe_3O_4 magnetic particles.

CuS nanoflakes by the hydrothermal process in alkaline conditions. Fig. 13(a) shows the shaping operation of magnetically garnished GR@CuS. The results illustrated the RL was -54.5 dB for the thickness of 2.5 mm at the frequency of 11.4 GHz, and the absorption bandwidth under -10 dB was 4.5 GHz. Fig. 13(b) shows the mechanism of MA, the entering of magnetic particles in GR sheets, and CuS nanoflakes worked as a significant factor in improving the microwave absorption characteristics [140].

In other cases, a number of researchers have investigated the effect of reduced graphene oxide (rGO) on ferrite, for instance, Zhang et al. prepared $\text{CoFe}_2\text{O}_4:\text{SnS}_2/\text{rGO}$ composite by hydrothermal technique. The results illustrated that the RL was -54.4 dB at the frequency 16.5 GHz for the thickness of 1.6 mm, the absorption bandwidth under -10 dB was 12 GHz, the dielectric loss was ($\epsilon_r = 7.3 - i2.7$), and the magnetic loss was ($\mu_r = 1 - i0.1$) [141]. Huang et al. prepared $\text{RGO}/\text{CoFe}_2\text{O}_4$ composite by hydrothermal technique. The results illustrated that the RL was -37.2 dB at the frequency 11.6 GHz for the thickness of 2.5 mm, the absorption bandwidth under -10 dB was 4.2 GHz, the dielectric loss was ($\epsilon_r = 7.1 - i2.8$), and the magnetic loss was ($\mu_r = 1 - i0.1$) [142]. Yunzhu

et al. collected 3D network layers of reduced graphene oxide on the surface of carbon nanotube/ Fe_3O_4 films by using an electrophoretic method. The results illustrated that the high absorption intensity for this composite was -50.5 dB at the thickness of 1.42 mm with the absorption bandwidth under -10 dB is 5.7 GHz. Fig. 14 illustrated that the manufactured microstructure of the interconnected network was made of reduced graphene oxide and carbon nanotubes with Fe_3O_4 magnetic particles [143]. Accordingly, it appeared that the graphene has elevated special surface areas that were so fit for loading ferrite nanoparticles [144–146]. Consequently like this hybrid is a unique candidate for utilization as the microwave absorber.

The summary of these studies which we were shown illustrates the ability of these composites to the microwave absorption, as these composites were distinguished as having wide bandwidth and lightweight with thin thickness. Table 2 is shown the microwave absorbing behavior of absorbent ferrite/carbon.

9. Summary and conclusions

The current review includes a discussion about the reflection loss mechanism which is due to firstly the dielectric loss mechanism which happens basically from conduction loss and polarization relaxations. Secondly, the magnetic loss mechanism which happens basically from natural resonance, domain wall resonance, and eddy current effect. In order to obtain efficient EM wave absorption materials, there should be efficient integration between dielectric and magnetic losses, so that to meet the requirement of the impedance matching condition along with the high absorption properties of the materials. Furthermore, the properties of hexagonal ferrites and spinel ferrites were highlighted. Hexagonal ferrites have a high crystalline magnetic field and that enhances their normal resonance in the upper GHz band, whereas the spinel ferrites have a low crystalline magnetic field and are used in microwave absorption applications that have a low resonance frequency. Also, the synthesis techniques of nano ferrites were highlighted and the advantages and disadvantages of each synthesis technique were pointed out. The data analysis indicates that the shape and size of various nanomaterials are directly related to the preparation method. Furthermore, the microwave absorption performances of nano ferrites are organized according to different parameters like precursor composition, combustion temperature, pH of the solution, etc. The current collection of scientific literature involves various groups of nano ferrites that interact with incident EM radiation in various models. The shape of the nano ferrites reaction with EM radiation is determined by the permeability and permittivity of a prepared substance. The researchers can estimate the RL of nano ferrites using complex permeability and permittivity related to substance thickness and frequency. Studies have shown that changing crystal structure, particle morphology, and a composite percentage will impact reflection loss value, and as well as absorption bandwidth. On the other hand, the results have shown the far better performance of composite materials with a nano ferrite core and a conducting polymer shell and composite materials (ferrite/carbon) than microwave absorbers of nano ferrite materials which are characterized by their lightweight and relatively low thickness. Eventually, understanding how to fabricate these materials is primary to control the characteristics of the final microwave absorber according to its potential applications.

Declaration of Competing Interest

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

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