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A review of mechanistic principles of microwave absorption by pure and composite nanomaterials

Mojtaba Rouhi [a], Zoleikha Hajizadeh [b], Reza Taheri-Ledari [b], Ali Maleki [b,*], Mohsen Babamoradi [a]

[a] Department of Physics, Iran University of Science and Technology, Tehran 16846-13114, Iran
[b] Catalysts and Organic Synthesis Research Laboratory, Department of Chemistry, Iran University of Science and Technology, Tehran 16846-13114, Iran

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ABSTRACT

Absorption, reflection, and transition are three modes of the electromagnetic radiation in facing the materials. An electromagnetic wave consists of electric and magnetic fields perpendicular to each other that do not depend on the material environment to propagate. The electrical and magnetic properties of the wave of the electromagnetic radiation are changed in the presence of microwave (or radio wave) absorbing systems. The different electrical permittivity and magnetic permeability in the secondary environment lead to the loss of the wave's energy and absorption of the wave. These processes have different performances, one in the form of heating and another in the form of resonance, which in turn will cause heat. It is observable that by using various elements or ferrites which have different structures, the ferromagnetic frequency could be changed. This is the most important factor in absorbing the waves from its magnetic aspect. Also, electrically, the rotation of the dipoles in the absorber with the aim of aligning themselves with the electric field of the microwave, will heat the absorbing molecules and attenuate the wave's energy. Overall, different magnetization states of the ferrites have been investigated and it was turned out that changes in ferromagnetic resonance frequency are due to the change in the determining factors in ferrite types. In this survey, an attempt has been made to find a relative insight into the classification of waves, absorbers and effective factors for microwave absorption.

1. Introduction

Today, technological advances are based on telecommunications technologies that have the ability to transmit information using waves [1]. This will cause the electromagnetic wave interference, that is used to transmit information [2]. The electromagnetic waves with various frequencies could be absorbed, reflected, and transmitted through different materials. These specific frequencies depend on the size and crystalline structure of the constituent particles [3]. Due to the disadvantages of the electromagnetic interference that threattens human health and electronic devices, the usage of microwave absorber materials is suggested in order to reduce their destructive effects [4,5]. Microwave absorbers currently have many applications in aviation, radiological safety, telecommunications technology, driverless vehicles industries and synthesis of nanomaterials [6–8]. These materials are used as coatings on equipment surfaces to eliminate or minimize reflection [3]. Therefore, many studies have been conducted to develop such materials with improved properties and performance [6]. The absorbers of the waves are capable to convert the received energy from electromagnetic wave to other forms of energy. In principle, microwave absorbers waste the wave's energy by dissipating process which is known as microwave absorption [9,10]. Various classifications for microwave absorbent materials are considered based on structure and composition [11], however, it should be noted that the intrinsic absorption, high magnetic permeability, adjustable electric properties, ability to change the absorption frequency broadband, high strength, and low weight, as well as high-temperature stability, are the most featured properties of the absorbers [11–16].

However, absorption by the materials includes important electrical processes, but the most effective parameter in the absorption rate is magnetic permeability [17]. The effects of the electrical permittivity and magnetic permeability due to the changes in the radiation environment are considered as the main bases for the calculation of the absorption rate after entering the waves into the absorber medium. When an

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* Corresponding author.
E-mail address: maleki@iust.ac.ir (A. Maleki).

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electromagnetic wave enters into the secondary medium, the electrical and magnetic properties of the radiated wave is changed proportionally to the amount of absorbed energy due to the presence of different materials. Generally, different frequency bands varying from a few hundred MHz to tens of GHz are applied in the instruments and electronic industries. In fact, the frequency ranges should be compatible with the application of the electronic device [18].

Based on the Scopus data references (Fig. 1), it can be seen that research in the field of the wave absorption rapidly grew in recent decades due to the rise of wireless technology and protection of the electronic devices. According to studies, many researchers, due to the increasing use of microwaves, have focused their studies on microwave absorbers to prevent electromagnetic interference. This article is submitted as a suitable reference that comprehensively explains the theoretical bases of the microwave absorption.

2. Mechanism of electromagnetic wave absorption

2.1. Electromagnetic wave

According to the wave theory, electromagnetic radiation was made up of both electric and magnetic fields by a wave-like phenomenon that propagates through space. These fields are propagating perpendicular to each other as the wave progresses. According to Maxwell's equations (Eq. (1)), propagation of the electric field forms a magnetic field, and subsequently, the magnetic field creates a variable electric field. The change in the size and position of the electric charge causes the electromagnetic wave to propagate (Fig. 2).

$$\nabla \times \mathrm{E} = -\frac{\partial B}{\partial t} \tag{1}$$

$$\nabla \times \mathrm{H} = J + \frac{\partial D}{\partial t}$$

Unlike the sound waves that need a material environment to propagate, the electromagnetic radiation has no mass and is transmitted without any need for materials. They can cross through both vacancies and the material environments. These features distinguish the electromagnetic radiation waves from other types of the waves [19]. The electromagnetic radiation comprises a wide spectrum of energy from very low to very high levels, which is called the "*electromagnetic spectrum*". Based on the frequency value and wavelength, the electromagnetic waves are classified as radio, microwave, infrared, visible light, ultraviolet, X-ray, and gamma-ray. The electromagnetic radiation is a current of photons that are transmitted in the wave form. Photons are fundamental particles and a mass of light energy with permanent movement. In fact, the amount of energy that the photon carries are determinative in the quiddity of the particles (which behave like a wave or particle). This phenomenon is known as wave-particle duality. The low-energy photons (like radio waves) have wave-like behavior, whereas high-energy photons (like X-rays) exhibit more particle behavior [20–22]. The reason for emphasizing microwave and radio waves is because of the wide range of applications that these types of waves can be involved in for transmitting information, and some of them are mentioned in Table 1. Other frequencies are not suitable for the uses mentioned in Fig. 3 due to having much weaker and much stronger frequencies that weaker frequencies do not have the ability to transmit the required information and stronger frequencies are harmful to human health and nature, therefore the absorbers of other frequencies of electromagnetic waves are less studied [23–25].

2.2. Bands and frequencies and applications

The frequency boundaries of the radio spectrum are a matter of convention in physics and are somewhat arbitrary [26]. The classification of microwaves and radiowaves was done based on International Telecommunication Union (ITU classification). The International Telecommunication Union refers to an organization that is responsible for the legislation and management of the frequency space and the determination of data and information exchange standards in the world. This classification is in the form of increasing the frequency or decreasing the wavelength, which is proportional to the amount of energy that the electromagnetic wave carries. Also, the applications of each band based on the frequency range were reported in Table 1 [18]. The ITU has defined a system of terms for electromagnetic frequencies used for radio waves, according to which radio frequency bands spread in the range between 3 kHz and 300 GHz.

2.3. Resonance

Every mechanical system tends to oscillate at the most possible amplitude at some frequencies. This condition and this frequency are called resonance and resonance frequency, respectively. In fact, the resonant frequency was selected by filtering other frequencies in its excitation state. As an example, due to the tuning of the knob by radio tuner, the natural frequency of the radio's electrical circuit changes. Also, the resonance occurred when this natural frequency was equal to the frequency of the desired radio station. So, the energy absorption reaches its maximum level and the sound of the same radio station is heard. Resonance usually refers to magnetic resonance, which is a crucial parameter for understanding the magnetic behavior of materials and contains very useful information which is used in many medical

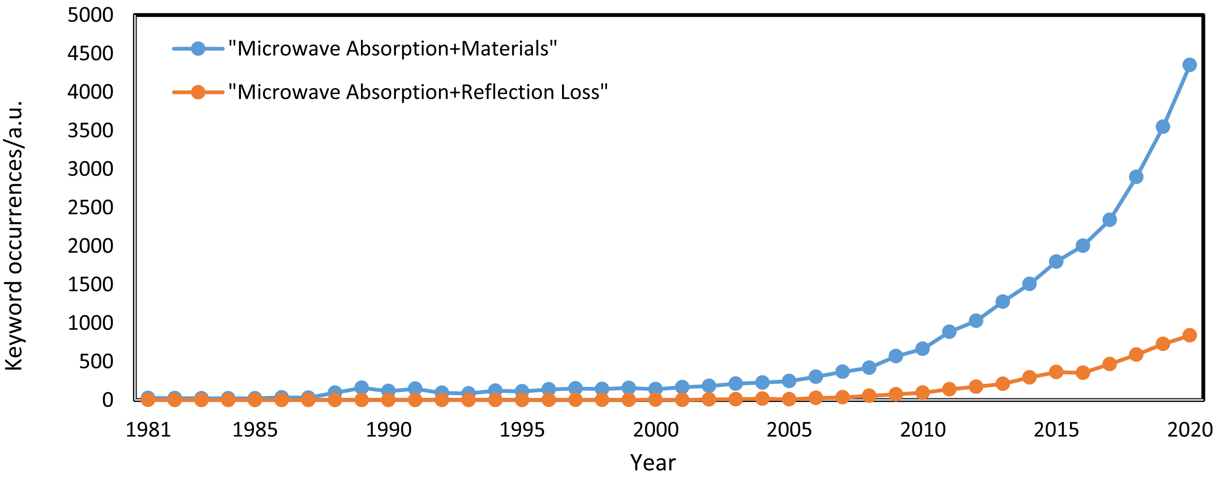

Fig. 1. Keyword occurrences as documented by Scopus for the given phrases by year, 1981–2020; the figure was adopted from Scopus data references.

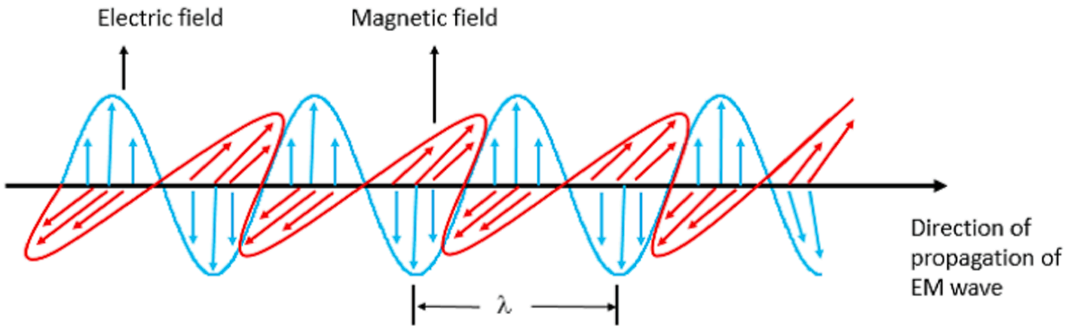

Fig. 2. Schematic presentation of directions and field orientations of the magnetic and electric fields. The time-varying electric field generates a magnetic field and vice versa.

Table 1
ITU classification of frequencies of microwaves.

Applications for each of frequency band	Frequency and Wavelength	ITU Band number	Abbreviation	Band name
- In the form of terrestrial waves in close distance communications - Non-Satellite Navigation Assist Systems	3–30 kHz 100–10 km	4	VLF	Very low frequency
- Longwave radio waves	30–300 kHz 10–1 km	5	LF	Low frequency
- Marine mobile communication systems - In the form of universal audio broadcast waves	300–3,000 kHz 1,000–100 m	6	MF	Medium frequency
- Using the Duct phenomenon for long-distance communication	3–30 MHz 100–10 m	7	HF	High frequency
- In the form of direct visibility communications on radars - Satellite Communications with Earth Terminal and Satellite to Satellite - Mobile radio systems	30–300 MHz 10–1 m	8	VHF	Very high frequency
- Direct View Microwave Radio Communications - Radar communication - Fixed and mobile satellite communications	300–3000 MHz 1–0.1 m	9	UHF	Ultra-high frequency
- Satellite communications of the k_u and k_a band	3–30 GHz 100–10 mm	10	SHF	Super high frequency
- High Frequency Microwave Communication for Cities and Low Distances - Multi-point Microwave Communication	30–300 GHz 10–1 mm	11	EHF	Extremely high frequency

devices (such as MRI) [27], industries, etc. Electron paramagnetic resonance (EPR), magnetic resonance of nuclei (NMR), and ferromagnetic resonance (FMR) are some of the resonant behaviors that will be further discussed [28].

2.3.1. *Electron paramagnetic resonance (EPR)*

EPR as a spectroscopic method was used for the chemical study of the samples with unpaired electrons. EPR was applied for the examination and understanding of the structure of organic, inorganic and metal compounds by studying the free radicals that exist in the compound. A single electron with the negative charge and specific mass has two types of motion; first, rotation of the electron around the nucleus and itself creates an orbital and spin magnetic momentum, respectively. Second, an external magnetic field (electromagnetic wave) causes the unpaired electrons to become paramagnetic and resonate at their resonant frequency, which is called "*EPR*" [29]. A modern EPR spectrometer is designed to measure with high sensitivity the microwave absorption in a sample as a function of the external applied magnetic field: the actual EPR experiment consists of scanning the magnetic field at constant microwave frequency until the resonance condition is fulfilled. Then a significant amount of energy is absorbed by the sample [30].

2.3.2. *Nuclear magnetic resonance*

The nucleus resembles an electron with a resonant torque. NMR occurs when the oscillating frequency of the magnetic field and the nucleus's magnetic momentum are exactly equal. Then, two fields are merged and the energy of the incoming radiation is transferred into the nucleus. This process causes a change in the nucleus spin and nuclear resonance is created [31]. The phenomenon of nuclear magnetic resonance was discovered in 1946 by Purcell and Bloch. It is based on the interaction of magnetic moments of nuclei of various atoms with magnetic fields. The magnetic moment of nuclei is associated with a nuclear spin, which is a form of angular momentum possessed by these nuclei. The value of nuclear spin is defined by a spin number. The nuclear magnetic moment associated with the nuclear spin depends on the properties of a nucleus and on its spin number [32].

2.3.3. *Ferromagnetic resonance (FMR)*

The excitation of ferromagnetic materials by a microwave (in the presence of an external magnetic field) leads to providing ferromagnetic resonance. Applying a magnetic field to the ferromagnetic materials causes precursor motion of matter around the external field at Larmore frequency. The synchronous application of the external magnetic field, and the electromagnetic wave with the Larmore frequency in the ferromagnetic materials make the resonance phenomenon, where the absorption of energy in the material occurs. Unlike the EPR and NMR, which operate on electron or nucleus spin, FMR is concerned with the magnetic domains of the ferromagnetic materials. The first FMR phenomenon was observed by Griffiths in 1946 [33]. The temperature-dependent magnetization of the ferromagnetic materials is at least three times more severe than the paramagnetic material. Although the ferromagnetic resonance broadband is usually very wide, it is the most sensitive type of spectroscopy to characterize the magnetic properties of

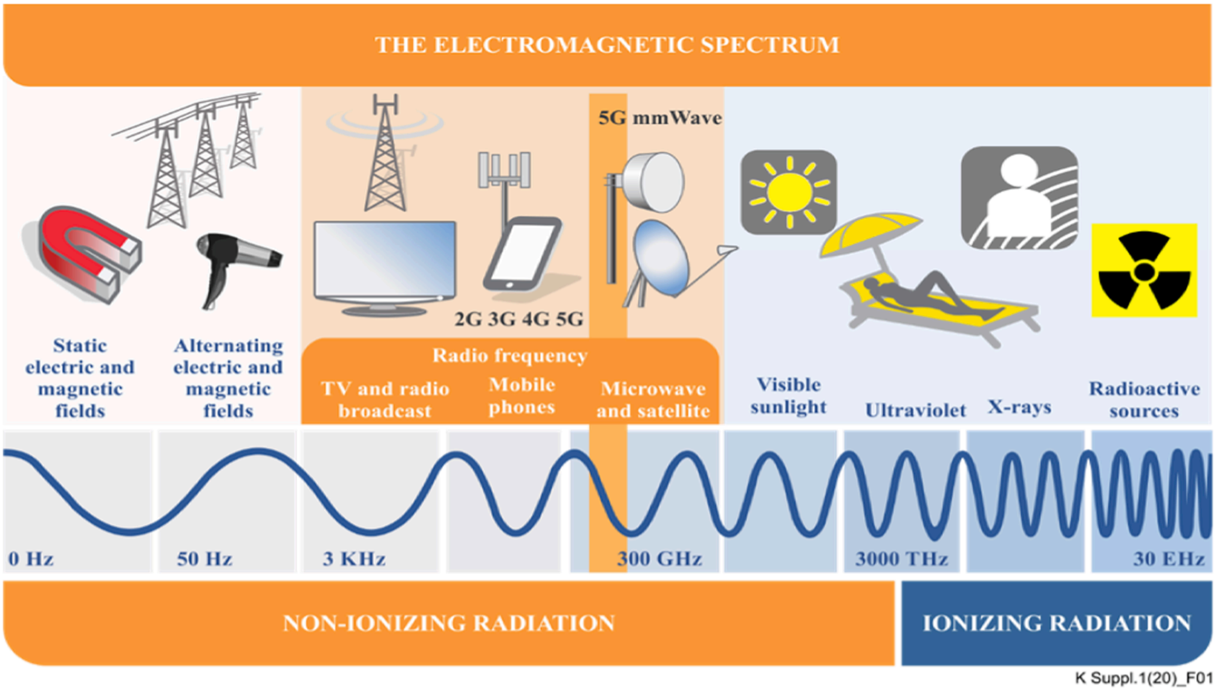

Fig. 3. ITU classification of frequencies of electromagnetic waves. This Figure was . adapted from www.itu.int

the materials. It is noteworthy that this phenomenon has been observed in ferromagnetic materials (their metals and alloys), as well as Ferrite materials (such as garnets) [28].

2.4. Microwave absorber materials for shielding against EMI

Microwave absorbing materials are used in electronic devices such as robots, mobile phones, telecommunication networks, satellites and military industries, etc. [30] and are used to prevent electromagnetic interference and protect against microwave pollution. two important factors in the characterization of microwave absorbers are the impedance [34] matching and absorption through their energy attenuation of the microwaves, which will be explained in the following mechanism of absorption [32,35].

The Absorbers can have three processes in microwave absorption; 1. Resistance loss, 2. Dielectric loss, and 3. Magnetic loss. According to numerous reports that have been reviewed in the past researches, microwave absorbers which can follow the three mentioned processes to absorb the waves are divided into four general categories, including magnetic materials such as magnetic metals, alloys, and oxide (Table 2), carbon-based materials (Table 3), composite materials like magnetic carbon composite (Table 4), and other nanomaterials with special structures such as MXene, sulfide, nitride, carbide and etc. (Table 5) [36,37]. Suitable microwave absorber materials are shown to have an acceptable absorption percentage and require sufficient bandwidth. For instance, the percentage of the wave absorption with a minimum reflection loss less than 10 dB, 20 dB, and 40 dB are about 90%, 99%, and 99.99%, respectively [1]. Metallic magnetic species, alloys, and ferrites materials have been extensively studied as an absorber systems [38–40]. The metallic magnetic materials indicate high amounts of

Table 2
Partially reported magnetic materials for EM microwave absorption.

Materials	Thickness /mm	RL/dB	Frequency /GHz	Bandwidth(<_10dB) /GHz	Ref.
Nd-Fe-Co-B	2	–23.1	9.8	4	[45]
Ni–Co	2.2	−36.5	14.77	6.55	[46]
Fe-Co	2	−13.8	10		[47]
Fe	1.7	−47.3	9.6	3.7	[48]
$Co_{0.66}Ni_{0.34}$	2.6	−54.6	4.5	10.08	[49]
$Co_{0.86}Ni_{0.14}$	1.8	−47.3	8.4	9.2	[49]
Ag-Fe /Fe_3O_4	3.5	−43.5	7.44	4.85	[50]
$NieMnO_2$	5	−20.4	3.9	1	[51]
Ni–B/Fe_3O_4	6	−28	5.3	4	[52]
$Bi_{0.8}Nd_{0.2}FeO_3$	2.4	−42	8.4	3	[53]
$CoFe_2O_4$	2.5	−34.1	13.4	2.6	[54]
Er-Ho-Fe	2.4	−37.26	5.68	1.2	[55]
$BaFe_{12}O_{19}$	2.48	−42.2	8	3.5	[56]
La-Nd-Fe	1.8	–32.5	9.8	3	[44]
Fe_3O_4	2	−28.1	13.2	3.8	[57]
$Pr_2Fe_{16}Ni$	3.5	–23.6	2.72	1	[58]
$Ni_{0.9}Ce_{0.1}Fe_{1.9}Zn_{0.1}O_4$		−21.44	15.52	6.44	[59]
NiO	7.9	−65.1	13.9	3	[60]
Fe–Ni	5	−24	0.5	0.6	[61]

Table 3
Partially reported carbon-based materials for EM microwave absorption.

Materials	Thickness /mm	RL/dB	Frequency /GHz	Bandwidth (<_10dB) /GHz	Ref.
Ppy/nano-EG	2.5	−48	13.4	13	[123]
rGO/PVA/CIP	3	−35.2	11.8	8.4	[124]
CNT	1.2	−20.4	14.6	4.51	[122]
Graphene	2.5	−37.8	12.3	4.4	[125]
PANI/CNT	2	−42.3	13.3	8	[126]
3D carbon	2.6	−52.6	15.8	8.6	[127]
PCHM/CNT	3.2	−34.6	3.6		[128]
SWNTs/SCPU	2	-22	8.8	2.7	[129]
H-HCNTs	3	−26	7.3	1.9	[130]
Ppy/CQDs	3.25	−27.82	6.93	1.2	[131]
PANI/CNT/ polystyrene	2	−45.7	18	6	[132]
Carbon/wax	2	−17.4	13	4.5	[133]
PANi/HCNTs	3.7	-32.5	8.9	3.9	[134]
r-GO	2	−6.8	6.5		[135]
CNTs/PANi	2	−41.37	13.28	8	[126]
MWCNT/ Graphene	2	−39.5	11.6	16	[136]
ACF	4	−62.8	6.3	2.5	[137]
ACF	4	-22.3	17.3		[138]
GF-piece// ACF	4	−16.1	9.1	5.4	[139]
GF	2	−35.5	13.2	11	[140]
CNT	–	−10	8.4	0.5	[141]

Table 4
Partially reported composite materials for EM microwave absorption.

Materials	Thickness /mm	RL/dB	Frequency /GHz	Bandwidth (<_10dB) /GHz	Ref.
PU/Bentonite	5	−20.16	8.92	1	[147]
PU/Fe/SiO_2	1.8	−21.8	11.3	3	[147]
PANI/Fe_3O_4	2	−15.8	15	8	[15]
PANI/Fe_3O_4/ CNTs	1.5	−59.9	16.4	3.9	[148]
Fe_3O_4/PEDOT	2	−30	9.5	2.8	[149]
$BaTiO_3$/PANI	3	−14.5	5.3	0.6	[150]
pyrrole/GNFs/ IONPs	$15*10^{-3}$	−24	X band	–	[151]
Fe_3O_4/SiO_2/ PVDF	2.5	−28.6	8.1	2	[152]
FPVDF/Fe_3O_4/ Ppy	2.5	−21.5	16.8	9.9	[9]
Polyphenyl amine/ barium ferrite	2	−28.9	18	5.6	[153]
PANi/$MnFe_2O_4$	1.4	−15.3	10.4	3.5	[154]
FeCo/C/$BaTiO_3$	2	−41.7	11.3	5.1	[155]
Fe_3O_4/PANI	2	−37.4	15.4	5	[10]
PANI/γ-Fe2O3	2	−15.3	14	0.6	[156]
Fe/C	2	-22.6	15	5.2	[157]
PNE/Mxene/ iron oxide	–	−43	11.5	4	[158]
RGO/ MWCNTs/ $ZnFe_2O_4$	5	-23.8	4.3	2.6	[159]
PANi/Fe/ Fe_3O_4/Fe_2O_3	3	−72.61	10.9	1	[160]
Co_3O_4/ MWCNTs/GO	5	−42.6	0.4	0.4	[161]
Cu-Mg-Ni/ MWCNT	1.5	−40	12.8	3.3	[162]
Fe_3O_4/rGO/ PANI	3.5	−45	8.5	12.2	[163]
RGO/Ga/ PEDOT	–	−34	X band	–	[164]
$BaFe_{12}O_{19}$/ PANI	2	−28	12.8	3.8	[17]
CoFe2O4/rGO/ SiO2	2	−24.8	5.8	1	[165]

magnetic saturation while their low electric resistance leads to huge loss of eddy current in the GHz band. In contrast, in the ferrite materials with higher magnetic permeability and electric resistance, the loss of eddy current is quite low [41–43].

2.4.1. *Magnetic materials: Ferrites, metals and their alloys*

Magnetic materials such as ferrites, metals and their alloys including metals such as Fe, Co, Ni and Mn, cause the wave to be absorbed by its magnetic mechanism due to high magnetic saturation. Z. Qiao et al. [44] synthesized the powders of $La_xNd_{2\text{-}x}Fe_{17}$ Through arc smelting and high-energy ball milling method to investigate the microwave absorption properties of La-Nd-Fe alloys and the minimum reflection loss is −32.5 dB at 9.8 GHz and the bandwidth less than −10 dB (Microwave absorption rate 90%) reaches 3 GHz with a thickness of 1.8 mm.

2.4.2. *Carbon-based materials*

Carbon based nanomaterials [62–68], including species such as graphene, CNTs, activated carbon, or various carbon polymers, are other microwave absorbers that absorb microwaves by dielectric loss due to their specific dielectric properties. Among the wide utilization of nanomaterials with spectacular characteristics, and applicability in different facets, namely, drug delivery [69–80], catalytic systems [81–104], Removal of contaminants [105–109], photocatalytic applications [110,111], tissue engineering [112–115], supercapacitor [116,117], solar cell [118,119], etc., carbon-based nanomaterials [120] are a group of microwave absorbing materials that can be effective in absorbing microwaves due to their conductivity through dielectric loss, which is itself affected by the imaginary part of electrical conductivity. In addition, the low density of carbon-based materials can make the absorber light in weight. Accordingly, various carbon-based materials have been studied as microwave absorbers, as can be seen in Table 3. Among the carbon-based microwave absorbers are nanotubes, carbon, graphene, carbon fibers and carbon polymers. In addition to the above-mentioned, the structure of basic carbon nanomaterials, which includes a specific cross-section, high surface porosity and heterogeneous structures, can cause polarization between crystal surfaces and, as a result, more dielectric loss [36,121]. For a typical example, J. Tang [122] studied the microwave absorbing properties of CNT the maximum absorption is as strong as −20.4 dB and the effective absorption bandwidth (refection loss ≤ −10 dB) reaches 4.51 GHz covering 45.1% of the entire measured bandwidth at only 1.2 mm thickness.

2.4.3. *Composition of carbon-based and magnetic materials*

In this type of hybrid materials, simultaneous application of carbon-based species (electric loss) and magnetic materials (magnetic loss) has resulted in high absorption efficiency of the microwaves. According to past studies, magnetic materials have a high ability to absorb microwaves due to acceptable magnetic loss. But high density has caused limitations in their major use as microwave absorbers [142], by making composites with carbon-based materials, researchers have tried to optimize their weight and increase the amount of dielectric loss to absorb more microwaves [6]. In the composition of magnetic materials such as microwave absorbing metal compounds which are often in the form of powders including iron, cobalt and nickel metals and their alloys [143] and ferrites with carbon-based materials due to the existence of advantages such as high working frequency and the high bandwidth has improved the properties of microwave absorbing materials [144,145]. Recently, Maleki et al. [146] performed an experimental study on the microwave absorption of ppy/HNTS/ Fe_3O_4 magnetic nanocomposite synthesized by hydrothermal method and the minimum reflection loss (RL) was −31.18 dB at 10.58 GHz for HPF1 nanocomposites corresponding for a thickness of 3 mm.

2.4.4. *Other species of absorbers with unique structures*

In addition to the referred absorber groups, there are other acceptable absorber systems including specific molecular structures like

Table 5
Partially reported other unique materials for EM microwave absorption.

Materials	Thickness /mm	RL/dB	Frequency /GHz	Bandwidth (<_10dB)/GHz	Ref.
PAni/HA/TiO_2/Fe_3O_4	5	−28.4	9.7	5	[16]
PANI/HA/TiO_2		−31	10	4.5	[12]
RGO/Ti_3C2TX	4	−21.2	11.8	3.7	[167]
Co_2P	1.1	−40	15.3	2.2	[168]
PANI/TiO_2/γ-Fe2O3		−45	14.6	6.6	[13]
$Ni_{0.53}Cu_{0.12}Zn_{0.35}Fe_2O_4/TiO_2$	2.2	−28	19.4	4.5	[169]
Fe/TiO_2	2	−16	11.7	4.1	[170]
MXene/PANI	1.6	−56.3	13.8	4.2	[171]
MoS_2/C	1.4	−44.7	13.1	3.3	[172]
CuS	1.8	−31.5	16.7	3.6	[173]
CuS	1.1	−17.5	17	3	[174]
Ti_3C_2TX/Ni	1.5	−47.06	12.4	3.6	[175]
Ti_3C_2Tx/PPY	3.6	−49.5	7.6	5.14	[176]
WS_2/NiO	4.3	−53.3	7	2.3	[177]
ZnO/MoS_2	2.5	−35.8	11.4	10.24	[178]
G–CdS	4	−48.5	10	12.8	[179]
ZnO/ Fe	3	−57.1	7.8	4.9	[180]
Al_4C_3@C	1.9	−47.1	15.7	5.5	[181]
ZnO nanowire-polyester	5	−12.28	10.75	1.5	[182]
Co/ZnO/Ti_3C_2Tx	2.4	−44.2	9.2	5.3	[183]

hierarchal, multi-shell, and other architectures. Zhuo et al. [166] developed a facile strategy for growing ZnO Dendritic Nanostructures that have been synthesized by a two-step chemical vapor deposition process and The value of minimum reflection loss for the composite with 50 vol% ZnO dendritic nanostructures is −42 dB at 3.6 GHz with a thickness of 5.0 mm.

As the most important absorber materials, ferrites, metals, and their alloys (which are listed in Table 2) have attracted huge attentions. The use of materials that each have their own structural, electrical, magnetic, and mechanical properties is important in the synthesis of compounds that are ultimately supposed to have an improved set of properties mentioned [6]. This is why this study focuses on this type of material and how bandwidth changes by changing their circumstances.

2.5. *Ferrites*

Ferrites are ceramic materials composed of a combination of iron oxide and divalent metals such as barium, strontium, lead, nickel, cobalt, and so on, including magnetic behavior similar to ferromagnets. They are hard and brittle and their color is gray or black. Ferrites are not very powerful magnets, but they are widely used in different industries due to their low cost. In this kind of materials, the magnetic moments of the atoms are against each other, but they do not completely neutralize each other because of their magnitude, and remained absolute magnetic moments. When these materials are exposed to an external magnetic field, all of these residual moments coincide with each other and the whole structure becomes magnetic. Most of these torques are often coherent after the removal of the external magnetic field, and the structure takes the form of a permanent magnet. The most well-known ferrite that has been used in compass construction for centuries is a natural magnet with the formula of Fe_3O_4, called “*magnetite*”. There are two trivalent and one divalent iron ion at the magnetite’s chemical structure. The orientation of the magnetic moment of the two trivalent iron ions is opposed and they neutralize each other. But, the magnetic moment of the divalent iron ion remains unaffected and creates a magnetic property in the material [184,185].

2.5.1. *Chemical formula and structure of ferrites*

The $M(Fe_xO_y)$ is a general formula for ferrites, in which “M” is a divalent metal like nickel, manganese, copper, barium, yttrium, etc. Ferrites with a polycrystalline structure consist of a large number of fine crystals with different orientations. The ferrites in terms of the crystalline structure are classified into spinel, garnet, and hexagonal [186].

2.5.2. *Spinel ferrites*

The spinel ferrites materials with the general formula of $M(Fe_2O_4)$ are soft magnetic materials that their magnetic field can change easily. Spinel ferrites materials are suitable for the building temporary magnets in which the crystal orientations do not affect the magnetization of these materials. Most of these materials have high static magnetic permeability and are applied as an absorber in the electronic industry at different frequencies [184,186,187].

2.5.3. *Garnet ferrites*

Garnet ferrite’s formula is $M_3(Fe_5O_{12})$ in which “M” is yttrium (Y) or trace elements like Gd or Lu. Their crystal structures are similar to garnet which includes a more complex structure than the spinel. Also, their magnetization has different results in various directions toward the external magnetic field. Garnet ferrites materials are classified as hard magnetic materials [184,185,187]. These materials with features such as high gyromagnetic properties and very low magnetic and dielectric loss, leading them to be applied in reciprocal and non-reciprocal microwave devices [187].

2.5.4. *Hexagonal ferrites*

The crystalline arrangement of the hexagonal ferrite materials is similar to a hexagonal prism with a vertical axis. Their general formula is $M(Fe_{12}O_{19})$ in which “M” is usually barium, strontium, or lead. As regards, the magnetization of the material along the vertical axis is easier than other axes. This species of ferrite material is known as hard-magnetic material. Indeed, the magnitude of their magnetic field or directions cannot be changed easily and is used to provide permanent magnets. This group of materials is also called hexaferrite. Hexaferrites are the basic matter for fabrication of the permanent magnets. Hexagonal ferrites are good microwave absorbers at GHz, due to high magnetization, great stability, low cost and easy fabrication of microwave absorbers. Hexagonal ferrites are composed of S blocks (spinel block) without alkaline earth metals, R blocks (hexagonal block) with alkaline earth metals plus two oxygen layers, and T blocks (hexagonal block) with alkaline earth metals plus 4 oxygen layers. Also, with different blocks arrangement, hexagonal ferrites are classified as different types of -M, -W, -Y, -Z, -X, and -U [184,186,188].

3. Microwave absorption process

By entering the electromagnetic waves into a secondary environment with different physical properties (electrical permittivity and magnetic permeability), the part of the wave will be absorbed due to the dissipative processes [189,190]. The absorbed waves appear as heat energy, which is the result of kinetic energy resulting from resonance. This process is the general mechanism of wave absorption. Relative electrical permittivity(ε_r), and relative magnetic permeability(μ_r) are non-dimensional quantities defined by Eq. (2) [191–194].

$$\varepsilon_r = \varepsilon' - i\varepsilon'' \tag{2}$$

$$\mu_r = \mu' - i\mu''$$

Their imaginary parts show the amount of energy dissipated and the attenuation of the electromagnetic wave emitted in the matter, and the amount of energy stored is indicated by the real part. According to the linear pass theory, the RL of electromagnetic wave (reflection loss) is obtained when the incident wave collides perpendicular to the surface of the monolayer materials (the absorber) with the metal background Eq. (3):

$$R_L = 20log\left|\frac{\mathrm{Zin} - \mathrm{Z0}}{\mathrm{Zin} + \mathrm{Z0}}\right| \tag{3}$$

Where, “Z_0” is the characteristic impedance of the free space, and “Z_{in}” is the input impedance at the intersection of matter and free space that is obtained by Eq. (4):

$$Z_{in} = Z_0\sqrt{\frac{\mu_r}{\varepsilon_r}}\tanh\left(i\frac{2\pi ft}{c}\sqrt{\mu_r\varepsilon_r}\right) \tag{4}$$

Where, “c” is the electromagnetic wave velocity in the free space, “f” and “t” are the frequency of the microwave and the thickness of the absorber, respectively. The reflection loss of an absorber is a function of the six characteristic parameters, as below:

f *and* t'' μ, μ', ε'', ε.

In other words, the samples made via different chemical or physical methods are put in the waveguide under the required frequency radiations, and the desired parameters are obtained. The RL value can be precisely calculated by the above equations.

3.1. Attenuate of electromagnetic waves

During the electromagnetic radiation, the absorption and losing energy happen by the imaginary part of the electrical permittivity and magnetic permeability (Fig. 2).

3.1.1. Absorption by the imaginary part of electrical permittivity

Unlike heat radiation, the thermal activity of microwaves deeply depends on the chemical composition of the materials that are exposed to the irradiation. Microwaves basically interact with polar molecules and charged particles. When the electromagnetic field of microwaves (also radiowaves) is alternated, it causes a rotation in the direction of the dipoles momentums to get align with the field orientation. A part of the energy of the waves increases the kinetic energy associated with these rotational oscillations. Eventually, it converts to the heat that is generated by the penetration of microwaves into the material due to the existence of friction. As a result, the dielectric heating phenomenon occurred [195–197].

3.1.2. Absorption by the imaginary part of magnetic permeability

The natural resonant frequency of the materials involves the aggregation of different types of resonant frequencies such as NMR, EPR, and FMR. The final resonant frequency of the absorber can be set according to their function, effectiveness, and frequency broadband. It should be noted that the most important determinative factor of the magnetic resonance frequency is ferromagnetic resonance frequency (FMR) in the materials, which also work for the ferrites. EPR as a specific type of resonance can be accrued in the presence of unpaired electrons and paramagnetic materials of the absorber. NMR is resonated at low frequencies (with frequencies in the MHz band) and it is neglected due to its low impact [31]. It should be stated that the absorption of the waves is performed by converting the electromagnetic energy of the wave to dissipative heat energy, when the absorber is exposed to the electromagnetic radiation and it intensifies.

3.1.3. Absorption by conduction loss

The electromagnetic absorption can be done by conduction loss induced by micro-current. The displacement of the electrons can be led to the loss of electromagnetic wave energy. This kind of absorption depends on the structure of the absorber’s crystalline lattice. In the structures where the electron needs more energy to move, more energy will be wasted and more energy of the waves will be absorbed [189,190] (Fig. 4).

4. Microwave absorption in a certain frequency band, especially for a few hundred MHz to a few GHz

Due to the existence of different species of ferrites, the resonant frequency of these particles needs to be investigated. According to the classification of hexagonal ferrites, the resonance frequency (-w type) in $BaM_2Fe_{16}O_{27}$ ferrite (M = Fe, Ni, and Zn) is around 36 GHz [188,198]. The Co positioning causes a change in the hexagonal structures. The resonant frequency in $BaCoxZn_{2\text{-}x}Fe_{16}O_{27}$ has been estimated to be in a range of 2.5–12.0 GHz [199]. The Microwave absorption of ferrite nanoparticles $Ba_{0.8}Al_{0.2}Co_{0.9}Zn_{1.1}Fe_{19}O_{27}$ is in a range of 9.62–13.29 GHz [200]. The $Ba_2Co_{2\text{-}x}Zn_xFe_{12}O_{22}$ resonance frequency is reduced from 1.5 GHz to 0.5 GHz through the addition of the Zn impurities [201]. Type -Z ferrites are soft hexagonal ferrite species that are very important. $Ba_3Co_2Fe_{24}O_{41}$ has relatively high magnetic permeability and is one of the most important magnetic ferrites for the absorption of the microwave waves in a range of 1.0–3.5 GHz [202]. $BaZn_xCo_{2\text{-}x}Fe_{28}O_{46}$ ferrite type -X with the resonant frequency of about 1.0 GHz, and $Ba_2(Zr_{0.5}Mn_{0.5})_xFe_{28\text{-}x}O_{44+0.25x}$ indicates a small microwave absorption in a range of 15.0–18.0 GHz [203]. Type –U ferrites with the formula of $Ba_4Ni_{2\text{-}x}Co_xFe_{36}O_{60}$ are microwave absorbers at high frequencies. Resonance frequency of $(Ba_{0.7}Bi_{0.2})_4(Co_{1\text{-}x}Ni_x)_2Fe_{36}O_{60}$ is around 11.3 GHz [204]. Type -M ferrites, such as $BaFe_{12}O_{19}$ and $SrFe_{12}O_{19}$, are important and permanent materials of the wave absorbers including a resonant frequency of ca. 40.0 GHz [205–207]. With M = CoTi the microwave absorption of $BaFe_{12\text{-}2x}M_xO_{19}$ is transmitted in a range of 26.0 to 40.0 GHz [208]. M−type microwave absorption of ferrite “Ba” is in a range of 18.0–26.5 GHz, which includes a composite form as $Ba_{(1\text{-}2x)}La_xNa_xFe_{10}Co_{0.5}TiMn_{0.5}O_{19}$ [209]. Simultaneous addition of Cu^{2+} and Zr^{4+} impurities to Ba/Sr hexaferrites causes a reflection loss peak at 11.1 GHz [38,39,210]. It can be seen that if we want to design an absorber for a certain range of microwave waves to minimize electromagnetic interference, we can use any of the items mentioned in its specific range of impact or its possible to use any of these items and compound it with other materials to do microwave absorption engineering and have a microwave absorption in the desired range.

4.1. Contributors to various resonance frequencies in ferrite materials

The changing elements in the ferrite materials cause to alter the magnetic resonance frequency. By studying this phenomenon and investigating the effect of the magnetic field on the electron, the following equation is obtained (Eq. (5));

$$\mathrm{S.B_{in}} = \mathrm{h}\upsilon \tag{5}$$

Where, “B_{in}” represents the internal magnetic field of determining element of the used ferrite, “h” is Planck’s constant, “υ” is the resonant frequency of the element, and “S” represents the spin vector. When the element is replaced, B_{in} is changed as well. Constantly, the spin vector and presence of the Planck constant on the other side of the equation shows that the resonance frequency of the composite change, too.

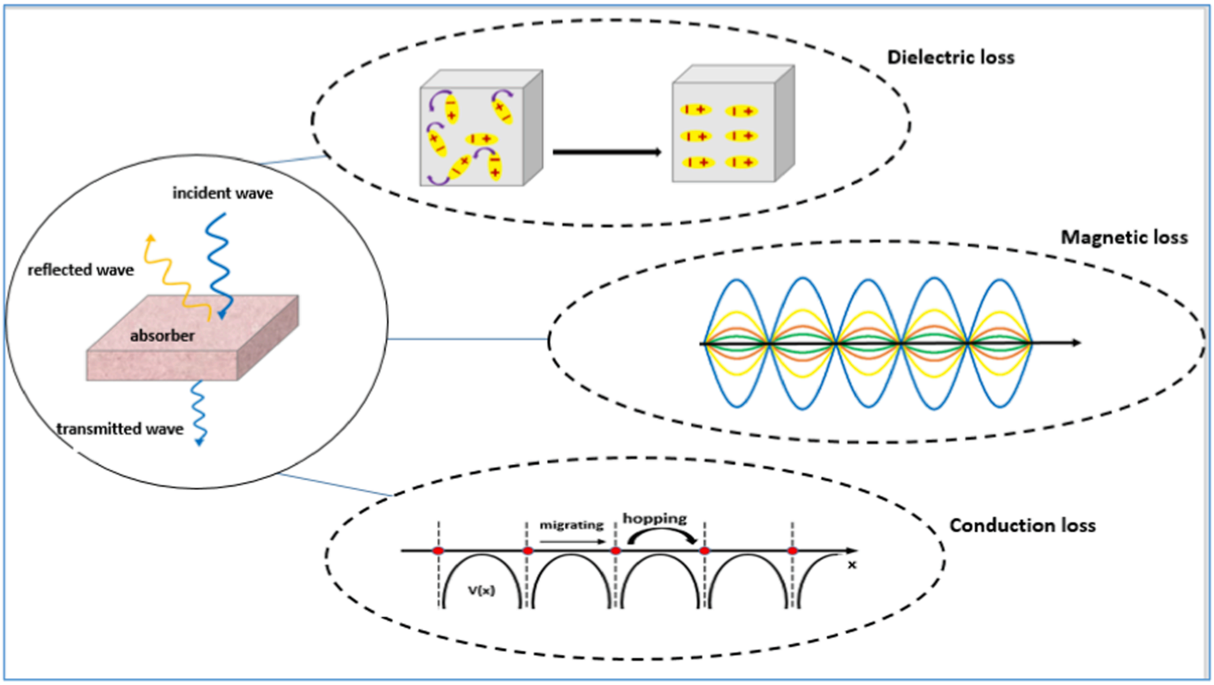

Fig. 4. The graphical designs for electrical, magnetic, and conductive processes of wave's energy dissipation.

[211,212]. B_{in} that is directly related to the magnetization of the used element is defined by Eq. (6) [213];

$$B_{in} = B_{field} + \mu_r M_{magnetization} \tag{6}$$

Where, "B-field" is the magnetic field of the irradiated microwave, "M" is the characteristic magnetization of determining element of ferrite, and "μ_r" is the relative magnetic permeability of the absorber. As an example, $BaFe_{12-x}Ru_xO_{19}$ with $\times \geq 0.3$ can be referred to, in which FMR is observed at 14.5 GHz in a range of 0.1–18.0 GHz and the reflection loss is very low with $RL \geq -10$ dB. In $SrFe_{12-x}Ru_xO_{19}$ species, strong microwave absorptions with $RL \leq -10$ dB are observed with $0.5 \leq x \leq 1.5$. The optimum RL is -32 dB observed in $\times = 1.0$ and 1.3, and the widest bandwidth is 6.55 GHz in $\times = 1.0$, with a thickness of 2.3 mm. In $\times = 0.5$, $RL \leq -10$ dB occurs in 14.2–18 GHz. It is observable that with changing the determining element (Ba changed to Sr) both absorption rate and resonant frequency are changed [186].

5. Conclusion

The wave absorption modality of the materials under electromagnetic radiation has been investigated. Electromagnetic radiation is a frequency range of the waves, which is classified based on the amount of energy carrying by the wave frequency. When the wave enters a new environment, the electrical and magnetic properties of the environment affect the wave behavior, resulting in the changes in the imaginary part of the electric and magnetic permeability of the wave, and further absorption. This process has been described with electrical and magnetic mechanistic considerations. From the electrical aspect, when a wave hits the material, it seeks to align dipole momentums in the material with the exposed electric field due to friction in the material's structure between its molecules (like the kitchen microwave). It causes a loss in the wave energy and turns it into heat. Each material has its own natural resonance that is caused by the interference of the various effective resonances such as EPR, NMR, and FMR. It should be noted that NMR is observed at the low frequencies around 100 MHz. EPR can be seen in the materials with unpaired electrons and in the paramagnetic part of materials. The ferromagnetic resonance (the most important part of the natural resonance) is available in ferrite materials. The absorption process and losing energy are happened by equalization of the resonant frequency of the incident waves and ferromagnetic, as the most important determinant of the natural resonance of the system. Wave absorption through conduction loss should be noticed, which is due to the displacement of the electrons that lead to the loss of the electromagnetic wave energy. Finally, the magnetic properties of ferrites and their magnetization rate are of high importance to be studied to determine the change in the resonance frequency for the use of the absorbers in different applications. Finally, in the field of microwave absorption, researchers should look for an absorber that its properties and performance for its users have been improved, which includes coverage of maximum frequency bandwidth and the best amount of reflection loss. It is expected that through this research, it will be possible to identify the various applications of different frequencies of electromagnetic waves and their required absorbers. In addition, due to the introduction of absorbers that operate in different ranges of the frequency of electromagnetic waves, it is possible to absorb a wide bandwidth of electromagnetic waves by using these absorbers layered on top of each other that can be used in a wide range of scientific fields. In order to achieve an absorbent that includes features such as affordable price, high bandwidth, lightweight, high absorption, and high temperature and chemical stability, many studies are conducted. The expected perspective of research in the field of microwave absorption includes other cases that may be challenging, in addition to those examined in past studies. Among these cases, we can mention limiting and changing the conditions in the absorption mechanism, which include the use of multi-layer absorbers or the use of non-conductive or non-magnetic materials in the absorbent material. Examining the functional properties of microwave absorbing materials in other scientific fields such as supercapacitors, batteries and solar cells for dual use can also be very attractive. Also, a more detailed investigation of the atomic properties of absorbers such as bandgap can be studied for a more detailed study of its effect on the amount of absorption and determining the absorption frequency of microwaves.

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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