

# A Review of Polyaniline-based Radar Absorbing Materials: Mechanism, Structure, Performance, and Future Applications

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**Abstract** - Electromagnetic waves caused by the development of radar technology, wireless communications and modern electronic devices has the potential to disrupt the function of the device and impact human health, so solutions are needed such as microwave absorbing materials or radar absorbing materials (RAM) that are light and thin, have high absorption strength, wide absorption band, strong damping, and good stability and environmental resistance. With polyaniline (PANI) as the main focus for microwave absorbing materials because it is a conductive polymer with high conductivity, good chemical stability, low density, and ease of synthesis. , this article will review the latest developments of PANI-based microwave absorbing materials composited with several other materials with a focus on the absorption mechanism, dielectric and magnetic characteristics, and the effect of composite formation on performance improvement. Based on the literature, PANI composites with ferrite, metal oxide, MXene, graphene, and MWCNT show reflection loss (RL) up to  $-88.8$  dB with effective the bandwidth reaches 14.6 GHz at a thin thickness of 1–3 mm. This performance improvement results from the synergy between dielectric and magnetic losses through the mechanisms of multiphase interface polarization, Debye relaxation, natural magnetic resonance, and impedance matching. optimal matching. With its lightweight, flexible characteristics and wide frequency range operation (S band– Ku band), PANI-based composites are excellent candidates for radar absorbing material (RAM), electromagnetic shielding (EMI shielding), and stealth technology applications in defense systems and modern electronic devices.

**Keywords:** Conductive Polymer Composite; Impedance Matching; Microwave Absorber; Polyaniline (PANI); Radar Absorbing Material (RAM)

## INTRODUCTION

The increasing exposure to electromagnetic wave radiation caused by modern electronic devices, radar technology and rapidly developing wireless communications, also has a negative impact on human health and poses a threat to military defense systems ( Ziadzi et al. , 2025; Guan et al. , 2025). Microwaves are part of the electromagnetic spectrum with a frequency of around  $10^8$  to  $10^{12}$  Hz which is widely applied in everyday life, for example television (470–860 MHz ), GSM/LTE mobile phones (800 MHz –2.6 GHz), Wi-Fi (2.4–5 GHz), microwave ovens (2.45 GHz), while modern radars operate in various frequency ranges, starting from the S-band

(2–4 GHz) used for weather radar and basic navigation, C-band (4–8 GHz) for weather radar and satellite communications, X-band (8–12 GHz) for navigation and military radar with medium resolution, to Ku-band (12–18 GHz) used for satellite communications and high-resolution radar (Wang et al. , 2018). For communication devices such as mobile phones, the ICNIRP (International Commission on Communications) standard on Non-Ionizing Radiation Protection ) sets a limit of body radiation exposure of 2 W/kg on a specific body part (e.g. the head) for 6 minutes, and 0.08 W/kg if calculated for the whole body over an average 30-minute period, which means the human body is only allowed to

absorb that amount of energy to remain safe assuming use is spread throughout the day (Mokhtar et al., 2018). Meanwhile, the FCC rules (Face-Centered Cubic) in the United States limits the SAR value of mobile phones to 1.6 W/kg based on average measurements on 1 gram of body tissue, so with this limit mobile phones are safe to use every day as long as their use does not exceed this standard because mobile phones are designed not to exceed the exposure threshold even if used for hours a day (Joy & Rajan Babu, 2025).

The development of conventional RAM (Radar Absorbing Material) faces significant challenges, such as limited bandwidth, high density levels, difficulty in obtaining small layer thicknesses, and high material costs, coupled with operational capabilities in extreme environments, such as corrosive conditions at sea or high-power devices with excessive heat, which are still obstacles to the widespread development of RAM (Duan et al., 2025). Ideal RAM works by minimizing reflection and maximizing the absorption of wave energy through the mechanisms of dielectric polarization, magnetic resonance, and impedance optimal matching (Ziadzi et al., 2025). For example, ferrite-based materials have good magnetic properties, but their performance is limited by the single loss mechanism and Snoek limitations (Cui et al., 2020). In addition, two-dimensional materials such as MXene have high absorption performance, but are hampered by the restacking phenomenon, which reduces their effectiveness (Zhu et al., 2025). With polyaniline (PANI) as the main focus for microwave absorbing materials because it is a conductive polymer with high conductivity, good chemical stability, low density, ease of synthesis and its ability in interfacial polarization, but still experiencing constraints on long-term stability and frequency selectivity, so other

materials are needed to be composited with Polyaniline (Ziadzi et al., 2025).

PANI with its low density, good environmental stability, and electrical conductivity in the range of  $10^{-2}$ – $10^0$  S/cm is very suitable for producing dielectrics. loss without sacrificing impedance matching. Pure PANI generally has a dielectric value loss in the range of 0.1–1.5 and can increase to 2–3 when composited with magnetic fillers or 2D materials, thus expanding the wave attenuation mechanism (Zhang et al., 2017; Shamsaddin Saeed et al., 2020; Zhu et al., 2025) PANI will increase magnetic loss, expanding bandwidth, and reducing reflection values loss (RL), when composited with functional fillers such as MXene, carbon, ferrite, or hexagonal boron nitride (h-BN) making it suitable for multi-band applications (S-, C-, X-, Ku-, up to Ka-band) (Dhanasekaran et al., 2025). Improving electromagnetic performance is very important, so research trends continue to develop to create environmentally friendly RAM materials based on biomass and polymers so that they can support the implementation of green energy technology (Guan et al., 2025). In the Industry 4.0 era, advances in additive manufacturing technology such as Selective Laser Sintering (SLS) are essential, enabling the fabrication of complex structures with high porosity, thus supporting absorption capabilities, and also enabling the integration of absorbent materials into high-tech components (Ziadzi et al., 2025).

By highlighting the characteristic properties of microwave absorbing materials including electrical properties, magnetic properties, interfacial polarization, bandwidth, and RL values, this literature review article will provide a conceptual framework of the latest research developments on PANI-based microwave absorbing materials and systematically map

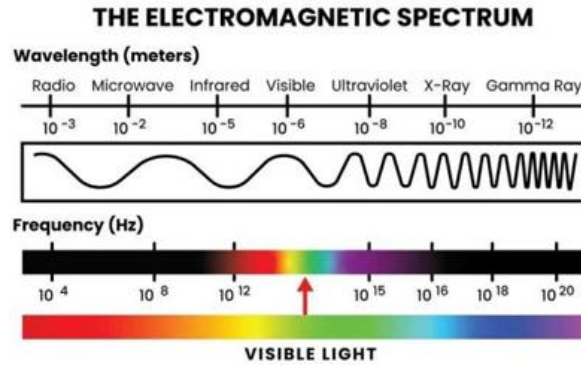
out the development strategy of conductive polymer-based RAMs to explore their potential applications and developments in the fields of radar, communications, and future electronic devices, so that this article will also present a broad scientific review, and provide guidelines for the design of lightweight, stable, effective, and environmentally friendly multifunctional materials to support stealth technology and the protection of modern electronic devices (Guan et al., 2025; Ziadzi et al., 2025). Increased exposure to electromagnetic waves caused by the development of radar technology, wireless communications, and modern electronic devices has the potential to disrupt device function and impact human health. The use of high-frequency electronic devices in communications, the military, and industry is also a cause of increased electromagnetic pollution. high (Mokhtar, et al., 2018; Raju, et al., 2021). Thus, research on microwave absorbing materials based on conductive polymers such as polyaniline (PANI) continues to develop to meet the need for shielding materials from electromagnetic interference (EMI) (Cui et al., 2019).

With the advantages of its high electrical conductivity, low density value, chemical stability, and ease of synthesis, PANI is the right candidate for increasing microwave absorption efficiency (Rehman et al., 2019). By integrating PANI into magnetic particles and two-dimensional structures, it is expected to provide synergy between interfacial polarization, dipole relaxation, and complex conductivity that increases absorption efficiency and expands the effective bandwidth (Zhang et al., 2017; Mokhtar et al., 2018). The approach taken is to composite PANI with inorganic or carbon-based nanostructure materials such as  $\text{TiO}_2$ ,  $\text{ZnO}$ ,  $\text{Fe}_3\text{O}_4$ ,  $\text{MoS}_2$ , and graphene to strengthen the dielectric and magnetic loss

mechanisms, as well as improve impedance matching between the absorbent material and the air (Zhang et al., 2018; Wang et al., 2018; Dhanasekaran et al., 2025).

## THEORITICAL REVIEW

Microwaves are part of the electromagnetic spectrum with frequencies between  $10^8$  and  $10^{12}$  Hz and wavelengths of approximately  $10^{-2}$  meters. These waves play a vital role in various fields such as communications, radar, navigation systems, and modern medical technology (He et al., 2021). However, increasingly massive use has given rise to serious problems in the form of electromagnetic interference (EMI), namely electromagnetic interference that affects the performance of electronic devices, reduces the quality of communication signals, and even causes health impacts due to excessive radiation exposure (Luo et al., 2016). As the number of electronic devices increases and the presence of 5G communication networks, the EMI problem is becoming more pressing, so the need for microwave absorbing materials that can suppress back radiation and convert electromagnetic energy into heat energy becomes very important (Kavoosi & Masoudpanah, 2025). As shown in Figure 1, microwaves occupy a position between radio waves and infrared waves on the electromagnetic spectrum. This range of wavelengths and frequencies allows them to interact with a wide range of objects, from communication devices and humans to biological materials. This explains why microwaves are widely used in modern technological systems, but they also have the potential to cause side effects in the form of EMI if not controlled (Zhu et al., 2025). By understanding the position of microwaves in the electromagnetic spectrum, the right strategy can be determined to develop effective wave-absorbing materials.



**Figure 1.** electromagnetic wave spectrum Source: Luo et al., (2016)

The electrical properties of microwave absorbing materials are determined by the complex permittivity ( $\epsilon = \epsilon' - j\epsilon''$ ). The value of  $\epsilon'$  indicates the material's ability to store electrical energy, while  $\epsilon''$  represents the ability to dissipate electrical energy into heat.

$$\epsilon' = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + \omega^2 \tau^2} \quad (1)$$

$$\epsilon'' = \frac{\epsilon_s - \epsilon_{\infty}}{1 + \omega^2 \tau^2} \omega \tau + \frac{\sigma}{\omega \epsilon_0} = \epsilon_p'' + \epsilon_c'' \quad (2)$$

where  $\sigma$  is the electrical conductivity of the material,  $\omega$  the angular frequency,  $\tau$  the relaxation time,  $\epsilon_0$  the vacuum permittivity,  $\epsilon_s$  the static dielectric constant, and  $\epsilon_{\infty}$  the dielectric constant at high frequencies. The dielectric constant ( $\epsilon_r$ ) describes how much the material is able to store electrical energy in an electric field, while the complex permittivity combines the energy storage ( $\epsilon'$ ) and energy dissipation ( $\epsilon''$ ) properties (Shamsaddin Saeed et al., 2020).

Dielectric loss can occur due to dipole polarization, electron conduction, or interfacial polarization. Polyaniline (PANI) as a conductive polymer offers advantages because its conductivity can be increased through a doping process with acid, so that the dipole polarization mechanism, interfacial polarization, and electrons hopping can be more effective. Dielectric value loss the tangent ( $\tan \delta = \epsilon''/\epsilon'$ ) in PANI is generally in the range of 0.1–1.5 and can namely material's ability to keep energy increase to 2–3 in composites with magnetic

fillers or 2D materials, which greatly supports the microwave attenuation mechanism. Thus, PANI is considered a material with high potential for use as a microwave absorber because it has light, flexible, stable properties, and is supported by a combination of electrical conductivity, dielectric constant, and complex permittivity that support its performance in microwave absorption (Jia et al., 2017; Zhang et al., 2017).

In addition to electrical properties, magnetic properties also play an equally important role in determining the performance of a microwave-absorbing material. The value of these magnetic properties is determined by the complex permeability, which can be expressed mathematically as:

$$\mu = \mu' - j\mu'' \quad (3)$$

In the equation mentioned,  $\mu'$  describes part real from permeability, magnetic. While that is,  $\mu''$  is part related imaginary with lost energy consequence various mechanism resonance, including spin resonance, magnetic domain resonance, and eddy currents (Raju et al., 2021). Permeability magnetic ( $\mu_r$ ) and permittivity electricity ( $\epsilon_r$ ) in collective determine impedance wave electromagnetic and the ability of materials to absorb energy waves. For magnetic materials that are often used, magnetization permanent also becomes factor important. Magnetization permanent is a phenomenon in which ferromagnetic materials still

magnetized even after external magnetic field removed (Huang et al., 2018). This property is very relevant in applications where materials are needed maintain characteristics magnetic without existence source energy external, as in some type of damper waves (Dhanasekaran et al., 2025). Polyaniline (PANI) is a conductive polymer that has been widely studied due to its unique chemical structure, good thermal and chemical stability, and its ability to undergo changes in oxidation and protonation levels so that its conductivity can be controlled through the doping process (Wang et al., 2022). PANI is relatively easy to synthesize at a relatively low cost and has been widely used in various fields, such as sensors, anti corrosion coatings, energy storage, and even as a microwave absorber. The combination of its dielectric and conductivity properties makes PANI able to effectively dampen electromagnetic radiation, especially when combined with other materials such as ferrite, graphene, or Fe<sub>3</sub>O<sub>4</sub> in the form of composites (Lin et al., 2023). Therefore, PANI is considered a promising candidate for use as Radar Absorbing Material (RAM) in various modern electromagnetic applications (Turczyn et al., 2020; Abhilash et al., 2023; Manna & Srivastava, 2021). Related to its electronic characteristics, the oxidation state of the polyaniline chain is usually expressed through the oxidation degree parameter, namely the ratio between the number of quinone units (quinoid, Q) to the total repeating units (quinoid + benzenoid, Q+B).

$$Y = \frac{N_Q}{N_Q + N_B} \quad (4)$$

where  $N_Q$  and  $N_B$  are the number of quinone and benzenoid units in the polymer chain, respectively. Conceptually,  $Y$  has a value between 0 (fully reduced — leucoemeraldine) and 1 (fully oxidized — pernigraniline), while emeraldine base (EB) is ideally around  $Y \approx 0.5$ . It should be noted

that the doping/protonation process (EB → emeraldine conversion) salt, (ES) increases the number of charge carriers (polarons / bipolarons) without significantly changing  $Y$ , so EB and ES can have the same oxidation state but different conductive properties due to the degree of protonation (Farias-Mancilla et al., 2016; Zhu et al., 2025). To relate  $Y$  to electrical properties in a simple way, a phenomenological approach can be used, stating that the electrical conductivity  $\sigma$  depends on the charge carrier density  $n$  and the mobility  $\mu$ . By introducing the degree of doping/protonation that modulates the fraction of active charged sites, the approach can be written as:

$$\sigma \propto n_{\text{carriers}}(Y, p) \mu \quad (5)$$

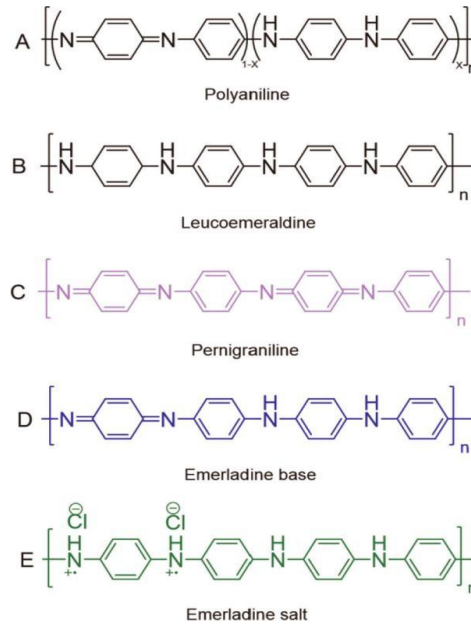
$$n_{\text{carriers}}(Y, p) \approx f(Y) \cdot g(p) \quad (6)$$

where  $f(Y)$  represents the availability of sites on the chain (the availability of units that can form polarons/bipolarons according to the oxidation state) and  $g(p)$  describes the protonation/doping effect that activates these sites to become charge carriers. This approach explains why ES (doped EB) shows much higher conductivity than pure EB even though the intrinsic oxidation value  $Y$  does not change drastically because  $g(p)$  increases  $n_{\text{carriers}}$  (Farias-Mancilla et al., 2016).

Polyaniline (PANI) is a conductive polymer that has four main phases depending on the oxidation level of its aniline units, namely leucoemeraldine, pernigraniline, emeraldine base, and emeraldine salt (Farias-Mancilla et al., 2016; Zhu et al., 2025). Leucoemeraldine is the most reduced form, with all aniline units in the amino state (-NH<sub>2</sub>). This phase has insulating properties with a very low conductivity ( $\sim 10^{-10}$  S/cm) and a bluish-white color, making it less suitable for microwave absorbing applications. In contrast, pernigraniline is the most oxidized form of PANI, where all units are in the

imino state (=N-). Although both are insulating properties with very low conductivity, pernigraniline has weaknesses

in terms of stability because it is easily degraded by the influence of oxygen and moisture.



**Figure 2.** Polyaniline Phase Source: Zhu et al., (2025)

The characteristic color of this phase is reddish purple. Although rarely used directly in practical applications, pernigraniline remains important in basic research related to the PANI oxidation process (Ruchi et al., 2024).

Between these two extreme forms is emeraldine base (EB) and emeraldine salt (ES) which plays an important role in the application of PANI material. Emeraldine Base is a semi-oxidized form containing a mixture of amino (-NH-) and imino (=N-) units, has semiconducting properties, is quite stable, and is often used as the initial step in the doping process. When EB undergoes protonation with acids such as HCl, H<sub>2</sub>SO<sub>4</sub>, or p-toluene sulfonate, the form will change to emeraldine salt. ES is known as the most conductive phase due to the presence of charge carriers in the form of polarons and bipolarons, with a conductivity reaching 1–10<sup>2</sup> S/cm. Its characteristic dark green color and high stability make ES the most widely applied form of PANI, especially in the fields of electronics, sensors, supercapacitors, and microwave absorbing

materials (Farias-Mancilla et al., 2016; Zhu et al., 2025).

Polyaniline (PANI) is often combined with magnetic or carbon-based reinforcement materials to improve microwave absorption performance. This aims to create a synergistic effect between dielectric loss, magnetic loss, and interfacial polarization. With this reinforcement strategy, PANI composites can achieve higher reflection loss (RL) and effective absorption bandwidth (EAB) compared to single PANI (Takai et al., 2020; Zhu et al., 2025).

PANI itself is one of the most widely studied conductive polymers due to its good stability, low production cost, and easy synthesis through the oxidative polymerization of aniline. This material also has a high dielectric constant, making it an important role in the dielectric mechanism. loss for microwave absorption (Wang et al., 2018). However, pure PANI only contributes through the dielectric effect without any magnetic components. loss, so its performance is still limited in wave absorbing applications (Saeed et al., 2020). Therefore, various further studies have

directed PANI to be composited with other materials that can add magnetic properties or increase interfacial polarization for optimal performance (Rehman et al., 2019).

Reflection Loss (RL) is the main parameter in assessing a material's ability to absorb microwaves. The RL value is calculated based on the reflection coefficient  $|\Gamma|$  that occurs at the interface between the material and free space, in accordance with the principles of electromagnetic waves and the theory of wave transmission in layered media. The mathematical relationship is written as:

$$RL(\text{dB}) = 20 \log|\Gamma| = 20 \log \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad (7)$$

where  $\Gamma$  is the reflection coefficient,  $Z_{in}$  is the input impedance of the material, and  $Z_0$  is the impedance of free space (377  $\Omega$ ). The value of  $|\Gamma|$  indicates the ratio of the reflected wave to the incident wave. If  $|\Gamma| = 0$ , it means that no wave is reflected and all energy enters the material. Conversely, the larger  $|\Gamma|$ , the greater the reflection that occurs at the surface. Therefore, RL can be considered as a logarithmic representation of the ratio of reflected wave energy. Physically, this relationship stems from Maxwell's theory of electromagnetic waves and the analysis of wave transmission in dielectric layers using the transmission model line. The RL equation is obtained by assuming the absorbing material as a layer with a certain complex permittivity and permeability, so that the reflection at the surface can be calculated through the concept of impedance matching. The smaller the difference between  $Z_{in}$  and  $Z_0$ , the smaller the reflection value that occurs, resulting in a low RL value (Manna & Srivastava, 2017; Wang et al., 2018). Bandwidth is the frequency range over which the RL value is lower than a certain threshold (usually  $-10$  dB).

The bandwidth is calculated from the difference between the maximum and minimum frequencies that meet the criteria:

$$BW = f_{max} - f_{min} \quad (8)$$

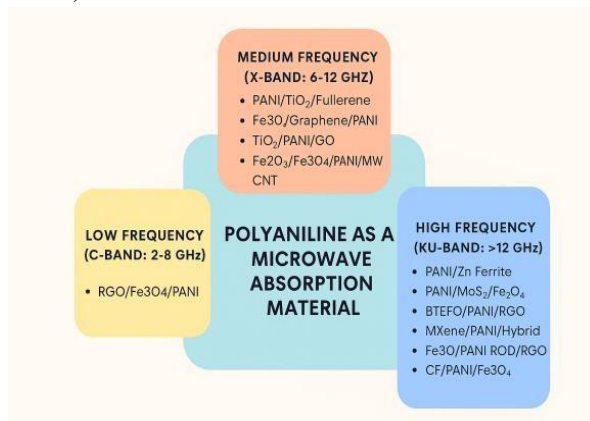
This parameter plays an important role because modern radar and communication systems operate not only at one frequency, but also at a fairly wide range of bands, such as S, C, X, and Ku. Absorbent materials that have a wide bandwidth are able to maintain absorption capabilities in various frequency ranges, making them easier to adapt for use in multi-band systems. Therefore, the development of absorbent materials is directed at not only achieving low RL but also expanding the working bandwidth so that their applications are increasingly relevant in the fields of defense and telecommunications (Zhang et al., 2017; Shamsaddin Saeed et al., 2020).

Impedance Matching indicates the correspondence between the intrinsic impedance of the absorbing material and the impedance of free space. The input impedance of the material is calculated using the equation:

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[ j \frac{2\pi f d}{c} \sqrt{\mu_r \epsilon_r} \right] \quad (9)$$

which means microwaves can enter the material without much reflection. This factor is very important because even if the material has a good loss mechanism, energy will not be absorbed if the waves are reflected on the surface due to mismatch. Therefore, the design of absorbing materials is often focused on achieving optimal impedance matching through engineering the composition, morphology, and controlling the ratio between complex permittivity and complex permeability (Joy & Rajan Babu, 2025).

Physically, impedance can be analogized as the "resistance" felt by electromagnetic waves when propagating in a medium, similar to the resistance experienced by electric current in a conductor (Rahimi-Nasrabadi et al., 2018). If the impedance value of the material approaches the impedance of free space, electromagnetic waves can enter easily, like an electric current flowing smoothly in a circuit with balanced resistance (Yang et al., 2019). On the other hand, impedance mismatch causes the wave to reflect, thus decreasing the absorption effectiveness. Thus, the achievement of impedance good matching is the main requirement for wave energy to actually enter the material and then be dissipated through the dielectric mechanism loss or magnetic loss (Joy & Rajan Babu, 2025).



**Figure 3.** PANI and its Composites as RAM (Over Several Frequency Ranges)

The mechanism of absorption of electromagnetic energy in materials occurs through two main pathways, namely dielectric loss and magnetic Dielectric loss loss is determined by the imaginary part of the complex permittivity ( $\epsilon''$ ), which is related to dipole polarization, interface polarization, and electron conduction. While magnetic loss is determined by the imaginary part of the complex permeability

( $\mu''$ ), which is affected by magnetic resonance, eddy currents, and magnetic domain relaxation. This parameter can be expressed through the loss tangent:

$$\tan \delta_e = \frac{\epsilon''}{\epsilon'}$$
 (10)

$$\tan \delta_m = \frac{\mu''}{\mu'}$$
 (11)

Materials with balanced  $\tan \delta_e$  and  $\tan \delta_m$  values have a better ability to dissipate microwave energy into heat. Thus, dielectric loss and magnetic Loss is the main key in increasing the effectiveness of absorption, because it plays a direct role in the energy attenuation process after the wave has successfully entered the material (Zhu et al., 2025).

## RESULTS AND DISCUSSION

Polyaniline with good microwave absorption ability using the interface polymerization method causes dielectric loss, making it difficult to achieve good impedance matching if only using polyaniline. By reviewing several studies of polyaniline- based microwave absorbing materials composited with various inorganic materials such as ferrite, metal oxides, and noble metals. The results show that differences in electromagnetic characteristics are influenced by the type of filler material and the synthesis method used. The results of several previous studies show an increase in conductivity properties, thermal stability, and microwave absorption effectiveness by adding inorganic materials to the PANI matrix through the mechanism of interface polarization and dielectric loss (Saini et al., 2018; Rehman et al., 2019; Saini & Shukla, 2020). Thus, further studies are needed to understand how compositional variations can affect the material's ability to absorb microwaves.

## Results

### *Microwave Absorption Characteristics of PANI at Low Frequencies (S–C Band, 2–8 GHz)*

In the low frequency range (S–C band, 2– 8 GHz), the microwave absorption characteristics of polyaniline (PANI) exhibit a distinctive behavior that underlies the formation of the absorptive properties of the material at higher frequencies. In this range, the relatively long electromagnetic wavelength causes the main interactions to occur in the macrostructure of the material, where the intrinsic resonance effects of the particles are not yet too dominant. Therefore, the interfacial polarization mechanism (Maxwell– Wagner) becomes the main mechanism of wave absorption, which arises from the differences in conductivity and permittivity between the phases. conductive PANI and magnetic fillers such as  $\text{Fe}_3\text{O}_4$  or conductive fillers such as graphene. This polarization creates an accumulation of charges at the interface boundary which generates a local field and *dielectric high loss* at low frequencies. Pure PANI basically has moderate to low electrical conductivity, so that microwave energy is not lost much through conduction mechanisms but rather is absorbed more through the process of space polarization of charges and dipole relaxation. Therefore, although the absorption capacity of pure PANI is still in the weak-moderate category, its performance can be significantly improved if it is composited with other materials that have magnetic and conductive properties, such as  $\text{Fe}_3\text{O}_4$ , graphene, or carbon, which function to increase *dielectric - magnetic coupling* and reduce the reflection value.

Research by Manna and Srivastava (2021) proved that in the RGO/  $\text{Fe}_3\text{O}_4$  /PANI composite system, wave absorption in the low frequency range increased sharply compared to the  $\text{Fe}_3\text{O}_4$  /PANI or RGO/  $\text{Fe}_3\text{O}_4$

binary composite, with a *reflection value of The maximum loss* (RL) reaches  $-64$  dB at a thickness of 0.45 mm, indicating that more than 99.999% of the electromagnetic wave energy is successfully absorbed. Under these conditions, the dominant mechanisms involve multiphase interfacial polarization between RGO–PANI–  $\text{Fe}_3\text{O}_4$ , dipole resonance, and space charge relaxation, which work synergistically to improve the *dielectric constant loss* ( $\epsilon''$ ) and *magnetic loss* ( $\mu''$ ). Basic reflection equation loss follows *transmission theory line*, which is in equations 7 and 9. where  $Z_0$  is the impedance of free space ( $\approx 377 \Omega$ ),  $\mu$  and  $\epsilon$  are the permeability and relative permittivity of the material,  $f$  frequency,  $d$  absorber thickness, and  $c$  speed of light. In this range, the composite complex permittivity ( $\epsilon'$ : 165–42,  $\epsilon''$ : 173–44) and permeability ( $\mu'$ : 0.93–0.23;  $\mu''$ : 0.97–0.24) show a decreasing trend with increasing frequency, indicating Debye relaxation and a decreasing ability of the dipole to follow the oscillatory field. However, the combination of high  $\epsilon''$  and  $\mu''$  values indicate good impedance matching, allowing electromagnetic waves to penetrate into the material and be absorbed efficiently. The results of *electromagnetic shielding effectiveness* (SE) also shows that  $\text{SEA} = 27\text{--}28$  dB,  $\text{SER} = 0\text{--}1.5$  dB, and  $\text{SET} = 28\text{--}29$  dB, indicating that the dominant mechanism is absorption, not reflection.

Several literatures also report that the thickness and doping level of PANI significantly affect the absorption efficiency, where increasing the thickness to reach the resonance condition of  $\lambda/4$  produces the highest RL in the range of 4–6 GHz, in line with the standing wave theory. Thus, at low frequencies, PANI begins to exhibit prominent absorptive properties, which can be significantly enhanced through composite engineering with magnetic and conductive materials to achieve an optimal balance

between conductivity, interfacial polarization, and impedance matching (Manna & Srivastava, 2021). Thus, at low frequency range (S–C band), PANI begins to exhibit prominent absorptive properties, especially after being composited with conductive and magnetic materials. This performance improvement is strongly influenced by the layer thickness, the even distribution of  $\text{Fe}_3\text{O}_4$  particles, and the quality of the interfacial interactions between the three components of the composite.

### ***Microwave Absorption Characteristics of PANI at Medium Frequencies (X-Band, 8–12 GHz)***

In the mid-frequency range (X-band, 8–12 GHz), the microwave absorption capability of polyaniline (PANI) shows a significant increase compared to that in the low-frequency range. This phenomenon is caused by the reduction of the electromagnetic wavelength, which enhances the interaction between the incident wave and the complex microstructure and morphology of the absorbing material. At this frequency, the wave energy is high enough to trigger intrinsic particle resonance, dipolar resonance, and coupling effects between the conductive-dielectric and magnetic phases in the composite. As a result, the interfacial polarization mechanism that was previously dominant at low frequencies is now combined with Debye relaxation, multipole resonance, and multiple internal reflection, resulting in a significant increase in dielectric loss ( $\epsilon''$ ) and total absorption efficiency.

PANI/TiO<sub>2</sub>/Fullerene composite developed by Mokhtar et al. (2018) shows *reflection the maximum loss* (RL) is  $-61.3$  dB at 9 GHz with a thickness of 2.5 mm. This value indicates that more than 99.999%

of the wave energy is successfully absorbed. The presence of TiO<sub>2</sub> as a dielectric phase increases the interfacial boundaries, strengthens the space polarization of the charge, and triggers Debye relaxation. Meanwhile, the fullerene C<sub>60</sub> acts as an electron acceptor, increasing conductivity and strengthening the *hopping mechanism conduction* in the PANI matrix. This combination results in a significant increase in dielectric loss ( $\epsilon''$ ) and strengthens the  $\lambda/4$  resonance condition, where the incident and reflected waves cancel each other out at an optimum thickness of about 2–3 mm.

Research by Jia et al. (2017) on TiO<sub>2</sub>/PANI/ Graphene Oxide (GO) with bouquet-like morphology also exhibits excellent response in the X-band. This composite achieves a maximum RL of  $-51.74$  dB at 9.67 GHz with a thickness of 3.12 mm and an effective bandwidth of 3.91 GHz. The tiered structure of TiO<sub>2</sub> /PANI/GO increases the number of active interfaces as well as multiple internal scattering that strengthens absorption. GO plays an important role in reducing the total conductivity of the system to achieve the desired impedance. optimal matching, while creating defects and charge traps that strengthen the Debye relaxation. Meanwhile, ZnFe<sub>2</sub>O<sub>4</sub>/PANI/GO (Qiao et al., 2019) showed a maximum RL of  $-58$  dB at 9.5 GHz with a bandwidth of 3.91 GHz and a thickness of 3.29 mm. The complex permittivity values ( $\epsilon' = 6-13$ ;  $\epsilon'' = 2.2-12$ ) indicate good charge storage and loss capabilities, while the complex permeability ( $\mu' \approx 1$ ;  $\mu'' \approx 0.4$ ) indicates the presence of spin resonance contributions. The main absorption mechanism originates from a combination of Debye relaxation, ion-exchange resonance ( $\text{Fe}^{3+}-\text{Zn}^{2+}$ ), and multiphase interfacial polarization between ZnFe<sub>2</sub>O<sub>4</sub>, PANI, and GO. In addition, Fe<sub>3</sub>O<sub>4</sub> / Graphene /PANI based composite by Wang

et al. (2018) showed a maximum RL of  $-43.7$  dB at  $10.7$  GHz with an effective bandwidth of  $5.4$  GHz ( $6.8$ – $12.2$  GHz) at a thickness of  $3$  mm. The presence of  $\text{Fe}_3\text{O}_4$  contributes to magnetic losses through natural resonance, while graphene and PANI provide electron conduction paths as well as dipolar polarization. The hybrid morphology of the nanorod – microsphere creates complex wave diffusion trajectories, reinforcing multiple reflection and extend the interaction time between the wave and the material. Another composite with a hybrid structure of  $\text{Fe}_2\text{O}_3 / \text{Fe}_3\text{O}_4 / \text{PANI}/\text{MWCNT}$  (Saeed et al., 2020) achieved the highest RL of  $-80.8$  dB at  $10.6$  GHz with a thickness of  $3.2$  mm and an effective bandwidth of up to  $8.3$  GHz ( $9.7$ – $18$  GHz). The presence of two types of magnetic particles with different spin arrangements strengthens the exchange resonance, while PANI plays a role in increasing conductivity and interfacial polarization. MWCNTs function as a conductive framework that expands the wave propagation path and improves the balance between dielectric and magnetic losses.

Overall, at mid-frequency (X-band), PANI and its derivative composites exhibit highly efficient microwave absorption performance, with RL values typically below  $-50$  dB and wide bandwidth ( $3$ – $5$  GHz) at relatively thin thicknesses ( $2.5$ – $3$  mm). The dominant mechanisms include dielectric loss through Debye relaxation, hopping conduction, multiphase interface polarization, dipolar resonance, and impedance matching controlled by the balance between permittivity ( $\epsilon'$ ,  $\epsilon''$ ) and permeability ( $\mu'$ ,  $\mu''$ ). By designing hybrid and hierarchical structures, such as the use of GO, ferrite, and metal oxides, the absorptive properties of PANI can be optimized to achieve high energy efficiency and a wide

frequency response. Thus, the X- Band region can be considered as the most ideal working domain for oxide- and ferrite- based PANI composites for microwave attenuation, electromagnetic shielding, and stealth applications. high performance coating (Jia et al., 2017; Mokhtar et al., 2018; Qiao et al., 2019; Xing et al., 2018).

### ***Microwave Absorption Characteristics of PANI at High Frequencies (Ku - Band, 12–18 GHz)***

In the high frequency range (Ku - band,  $12$ – $18$  GHz), the microwave absorption capability of polyaniline (PANI) shows a significant increase compared to low and medium frequencies. This increase occurs due to the reduction of the electromagnetic wavelength which increases the interaction between the incident wave and the nanocomposite microstructure, triggering multipole resonance, Debye relaxation, and synergistic coupling between the dielectric and magnetic phases (He et al., 2021).

PANI/  $\text{ZnFe}_2\text{O}_4$  composites from Xing's research et al. (2018) showed extraordinary performance with *reflection values the minimum loss* (RL) is  $-54.4$  dB at  $17.6$  GHz and the optimal thickness is  $1.4$  mm. These results indicate that at high frequencies, PANI acts as a conductor that improves *the dielectric loss*, while the  $\text{ZnFe}_2\text{O}_4$  particles act as natural magnetic resonance centers *which strengthen the magnetic loss*. The interfacial interaction between PANI and  $\text{ZnFe}_2\text{O}_4$  creates significant space polarization of charges and broadens the wave diffusion path, resulting in high energy absorption efficiency.

Similar performance was also reported by Ma et al. (2019) on  $\text{Fe}_3\text{O}_4 / \text{PANI}$  rod /RGO composites, which have a very wide effective absorption bandwidth reaching  $14.6$  GHz with an RL value below  $-10$  dB.

The combination of rGO as a conductive phase,  $\text{Fe}_3\text{O}_4$  as a magnetic resonance center, and PANI as a bridge between the phases produces an impedance excellent matching and synergistically improves dielectric and magnetic losses. In addition, Luo et al., (2019) reported that the  $\text{BaTb}_{0.2}\text{Eu}_{0.2}\text{Fe}_{11.6}\text{O}_{19}/\text{PANI}/\text{RGO}$  composite was able to achieve a minimum RL of  $-60.9$  dB at  $16.4$  GHz with a thickness of only  $1.95$  mm and an effective  $4.2$  GHz bandwidth. This advantage results from the doping effect of  $\text{Tb}^{3+}$  and  $\text{Eu}^{2+}$  ions in  $\text{BaFe}_{12}\text{O}_{19}$ , which strengthens the magnetic anisotropy, as well as the contribution of RGO, which improves conductivity and reduces surface reflection. PANI in this system functions to increase the impedance matching through dielectric enhancement relaxation.

In the  $\text{PANI}@/\text{MoS}_2@/\text{Fe}_3\text{O}_4$  nanowires composite, Zhang's research results et al. (2018) showed an RL value of  $-49.7$  dB at a thickness of  $1.3$  mm with an effective bandwidth of  $6.48$  GHz. The hierarchical structure of the nanowire allows for multiple effects. strong multipole reflection and resonance, while  $\text{Fe}_3\text{O}_4$  nanoparticles add magnetic loss without sacrificing the lightness and flexibility of the material. PANI plays a role in maintaining conductivity and strengthening interfacial polarization, while  $\text{MoS}_2$  increases Debye relaxation and suppresses the skin effect. Zhang et al. (2021) also developed a hybrid  $\text{CF}@/\text{PANI}@/\text{Fe}_3\text{O}_4$  nanocomposites, which achieved a minimum RL of  $-46.86$  dB at  $2.7$  mm with an effective absorption Wide bandwidth. The combination of carbon fiber (CF) as a conductive frame, PANI as a conducting polymer layer, and  $\text{Fe}_3\text{O}_4$  as a magnetic component creates a double attenuation mechanism through dipolar

polarization, magnetic resonance, and eddy current loss.

In a study by He et al. (2021), MXene/PANI- based materials also show great potential as microwave absorbers at high frequencies. The two-dimensional structure of MXene combined with PANI forms a layered system with a *dielectric - magnetic interface*. The MXene surface rich in functional groups ( $-\text{OH}$ ,  $-\text{O}$ ,  $-\text{F}$ ) strengthens interfacial polarization, while PANI provides a conductive path for electron migration, resulting in an ideal balance between permittivity and permeability. This material is very effective for EMI shielding and microwave applications absorption because it shows impedance good matching at Ku -band frequencies.

Overall, in the high-frequency region (Ku -band), PANI-based materials exhibit superior microwave absorption performance, with RL values generally below  $-50$  dB and effective *bandwidths* between  $4-7$  GHz at thin thicknesses ( $1-3$  mm). The dominant mechanisms include dielectric loss due to Debye relaxation, hopping conduction, multiphase interface polarization, natural magnetic resonance, and *impedance balancing matching* between  $\epsilon$  and  $\mu$ . The design of hierarchically structured hybrid nanocomposites such as the combination of rGO, ferrite, MXene, and  $\text{MoS}_2$  has been shown to enhance the absorption performance and make PANI a prime candidate for stealth applications. high- performance electromagnetic wave coating and shielding (Xing et al., 2018; Ma et al., 2019; Luo et al., 2019; Zhang et al., 2018, 2021; He et al., 2021).

**Table 1.** microwave absorption performance over a wide range of frequencies

Material	Bandwidth			Reflection Loss (RL)	Properties of Electricity	Magnetic Properties	Ref
	C-Band	X-Band	Ku - Band				
PANI/TiO <sub>2</sub> / Fullerene		0.5–18 GHz		-61.3 dB at 9 GHz	$\sigma = 1.7 \times 10^{-1}$ S/cm; $\epsilon' \approx 10.1$	-	1
Nanocomposites (Ni <sub>0.48</sub> Cu <sub>0.12</sub> Zn <sub>0.4</sub> Fe <sub>2</sub> O <sub>4</sub> (NCZ)/ Polyaniline			8.2–18 GHz	-42.10 dB at 9.35 GHz	$\epsilon' = 10.9, \epsilon'' = 3.007$ .	$\mu' = 1.45, \mu'' = 1.313$	2
PANI/ Zn Ferrite			2–18 GHz	-54.4 dB at 17.6 GHz	$\sigma = 1.64 \times 10^{-2}$ S/cm	$\mu' \approx 1.25; \mu'' \approx 0.35$	3
PANI/MoS <sub>2</sub> /Fe <sub>3</sub> O <sub>4</sub>			2–18 GHz	-49.7 dB at 16.8 GHz	$\epsilon' \approx 12-16; \epsilon'' \approx 4-8$	$\mu' \approx 0.9-1.1; \mu'' \approx 0.2-0.4$	5
Fe <sub>2</sub> O <sub>3</sub> / Fe <sub>3</sub> O <sub>4</sub> /PANI/MWCNT		8–18 GHz		-88.8 dB @ 10.6 GHz	$\epsilon': 17 \rightarrow 11; \epsilon'': 2 \rightarrow 6$	Ms = 42.3→29.5 emu /g	7
Fe <sub>3</sub> O <sub>4</sub> / Graphene /PANI		6.8–12.2 GHz		-43.7 dB @ 10.7 GHz	$\epsilon': 12.8 \rightarrow 6.8$	Ms: 22.2 emu /g	8
TiO <sub>2</sub> /PANI/GO ( bouquet )		2-18 GHz		-51.7 dB @ 9.7 GHz	$\epsilon' \approx 7-11; \epsilon'' \approx 2-5$	-	11
ZnFe <sub>2</sub> O <sub>4</sub> /PANI/GO			1–18 GHz	-58 dB @ 9.5 GHz	$\epsilon' = 6-13; \epsilon'' = 2-12$	$\mu' \approx 1; \mu'' \approx 0$	12
CF@PANI@Fe <sub>3</sub> O <sub>4</sub>			2–18 GHz	-46.9 dB @ 9 GHz	$\epsilon' \approx 10-20; \epsilon'' \approx 3$	$\mu' = 1-1.2; \mu''$ increases	13
RGO/ Fe <sub>3</sub> O <sub>4</sub> /PANI	2–8 GHz			-64 dB @ 2 GHz	$\epsilon' = 165 \rightarrow 42; \epsilon'' = 173 \rightarrow 44$	$\mu' \approx 0.9 \rightarrow 0.2$	21
MXene /PANI hybrids			11.84–17.76 GHz	-65.6 dB @ 13.9 GHz	$\sigma = 325-59,900$ S/m	-	22
BTEFO/PANI/RG O			2–18 GHz	-60.9 dB @ 16.4 GHz	$\epsilon' = 4.5 \rightarrow 10.5; \epsilon'' = 1.3 \rightarrow 9$	Ms $\approx 13.9$ emu /g	23
Fe <sub>3</sub> O <sub>4</sub> /PANI rod/ rGO			7.9–18 GHz	-46.0 dB @ 13 GHz	$\epsilon' \sim 10.5; \epsilon'' \sim 6.0$	Ms Fe <sub>3</sub> O <sub>4</sub> : 60 emu /g	41

The results table and discussion show that polyaniline (PANI) based composites when combined with inorganic materials such as ferrite, metal oxide, graphene, MXene, and MWCNT produce excellent microwave absorption performance over a wide range of frequencies (Mokhtar et al., 2018). The best absorption efficiency value, namely at a percentage of more than 99.99%, shows a reflection value The highest loss (RL) is up to -88.8 dB with a bandwidth of up to 14.6 GHz (Shamsaddin Saeed et al., 2020). Performance enhancement caused by the synergy between dielectric ( $\epsilon''$ ) and magnetic ( $\mu''$ ) losses resulting from the multiphase interface polarization mechanism, Debye relaxation, natural magnetic resonance, and impedance good

matching (Qiao et al., 2019). Composites such as Fe<sub>2</sub>O<sub>3</sub> / Fe<sub>3</sub>O<sub>4</sub> /PANI/MWCNT and ZnFe<sub>2</sub>O<sub>4</sub> /PANI/GO show superior properties in the X– Ku band range ( Zhang et al. , 2018), while the MXene /PANI and PANI/ ZnFe<sub>2</sub>O<sub>4</sub> systems produce optimal absorption at high frequencies with thin material thickness, so they have high potential for radar absorbing material (RAM) and electromagnetic shielding applications (Xing et al. , 2018; He et al. , 2021). Overall, these results confirm that increased structural heterogeneity, numerous active interfaces, and a balance between permittivity and permeability are key factors in producing lightweight and efficient PANI-based microwave absorbing materials (Luo et al., 2019; Manna & Srivastava, 2021).

## CONCLUSION

Polyaniline (PANI) has been proven to be a very potential microwave absorbing material due to its combination of conductive properties, chemical stability, and structural flexibility. Previous studies have shown that the performance of PANI can be significantly improved through the formation of composites with inorganic materials such as ferrite, metal oxides, MXene, graphene, and MWCNTs. The synergy between dielectric and magnetic losses generated by the interfacial polarization mechanism, Debye relaxation, natural magnetic resonance, and impedance balance matching allows the reflection value to be achieved loss (RL) up to  $-88.8$  dB with a wide absorption bandwidth reaching 14.6 GHz at a thin thickness of 1–3 mm. This confirms that increasing structural heterogeneity and the number of active interface boundaries are the main keys in strengthening the efficiency of electromagnetic wave energy absorption. With its lightweight, efficient characteristics, and its ability to operate in a wide frequency range (S– Ku band), PANI-based composites are excellent candidates for radar absorbing material (RAM) applications, electromagnetic protection (EMI shielding), and stealth technology in the defense industry and modern electronic devices.

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