

## A Review of Recent Advancements in Materials that Absorb Microwave Radiation and Are Derived from Complicated Substances

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**Abstract:** Materials that absorb microwaves are widely used in both the military and the civilian world. Moreover, their importance has increased due to their ability to reduce electromagnetic pollution. High porosity, low density, a wide conjugated backbone, a narrow energy band gap, suitable conductivity and relaxation losses, and a significant specific surface area are all necessary for the ideal conjugated organic polymer for microwave absorption. The types of conductive polymers used as materials that absorb microwaves and their composites to increase their effectiveness are described in this review. Additionally, the structural properties of pure carbon-based microwave-absorbing materials and other conjugated structures with heteroatoms in their chains are analyzed, along with current developments in synthetic techniques. The main mechanisms by which conductive polymers and their composites absorb microwaves are examined, along with particular techniques for modifying these features, such as metamaterial and quasi-antenna qualities. This review offers new possibilities for tailoring conjugated polymers based on their primary mechanisms and clarifies the design of low-density, high-performance microwave-absorbing devices.

**Keywords:** conductive polymer, microwave-absorbing materials, dielectric structures, conjugated polymer, metamaterial, quasi-antennas

### Introduction

By reducing electromagnetic pollution, microwave-absorbing materials are crucial for protecting both human and environmental health (Peymanfar et al., 2021a). Magnetic and dielectric losses, which convert electromagnetic energy into thermal energy, are crucial elements attenuating microwaves (Yang et al., 2022a). In order to protect against electromagnetic pollution, considerable efforts have been made to design materials that absorb microwaves.

High-performance microwave-absorbing materials with robust absorption characteristics and a wide effective bandwidth have been the focus of recent research. According to several studies, the main components of the matrix's electromagnetic wave-absorbing materials are metal nanoparticles, ceramics, and conductive polymers (Lv et al., 2022). Wide bandwidth, low matching thickness, lightweight and economical properties, strong absorption capabilities, and simple testing conditions are all features of an ideal microwave-absorbing structure. To enable good impedance matching, an efficient microwave-absorbing structure needs to have both dielectric and magnetic characteristics. By creating exchange and natural resonance, magnetic structures increase permeability for electromagnetic attenuation (Zhang et al., 2021a). By producing metamaterial properties, heteroatoms in conductive polymers increase permeability (Peymanfar et al., 2022). The most popular and effective conductive polymers with heteroatoms in their architectures that are used to create components that absorb microwave radiation include polyaniline, polythiophene, polypyrrole, and polydopamine (Das and Prusty, 2012). Additionally, by increasing polarization loss and producing secondary fields, the size and arrangement of electromagnetic absorbers have an impact on the optimization of microwave-absorbing qualities (Peymanfar et

al., 2018). By changing the morphology of the nanostructure, the energy band gap—a crucial factor in determining the conductive and dielectric loss properties—is modified (Peymanfar et al., 2018).

The trajectory of electron transmission and penetration, multiple reflections, scatterings, conductive loss, and relaxation loss can all be affected by morphological changes in conjugated conducting polymers that change orbital orientations (Ding et al., 2012). Significant dielectric loss characteristics are displayed by conjugated organic molecules. There are three known methods for increasing this class of materials' dielectric loss capacity: 1) Doping materials with heteroatoms to produce unpaired spins and control conductive loss, induce magnetic order, improve dipole polarization, improve quasi-antenna characteristics and impedance matching, and adjust the energy band gap; 2) Compositing conductive polymers with functional materials to improve impedance matching, establish permeability, and facilitate other crucial microwave-absorbing mechanisms; and 3) Increasing the specific surface area by increasing porosity, increasing the surface area-to-volume ratio to mitigate polarization loss, and ultimately decreasing density by lowering the filler content.

New materials known as metamaterials have recently gained recognition for their promise in the optical, plasmonic, and electromagnetic wave absorption domains. Metamaterials offer remarkable absorption capacities and inverse electromagnetic responses. By increasing the propagation of incident waves within the absorbing medium, metamaterials provide electric and magnetic resonances, improving impedance matching and optimizing reflection loss (Ding et al., 2012). Interestingly, polarized structures exposed to alternating fields can behave as quasi-antennas, producing metamaterial properties and secondary fields (Yan et al., 2018).

The microwave-absorbing properties of various conjugated conductive polymer types were evaluated in this review. To make future study easier, the synthesis procedures, structural characteristics, and microwave-absorbing mechanisms of this kind of material were highlighted. New developments in metamaterial and quasi-antenna properties related to conducting organic polymers were then investigated. In order to create lightweight, high-performance absorbers, the mechanisms behind the microwave-absorbing effectiveness of conjugated organic polymers and related structures, as well as their structural features, were examined. This, in turn, broadened the scope of innovative microwave-absorbing advancements and highlighted advanced research in conductive polymers.

### **Mechanisms Enhancing Microwave Absorption in Conductive Polymer Structures**

Conductivity and polarization losses are the main processes that enable microwave attenuation in conjugated carbon-based materials (Pattanayak et al., 2021; Huynen, 2022). The main factor influencing how the polarization loss features are adjusted is morphology (Peymanfar et al., 2021c). Moreover, dipole polarization is caused by heteroatoms and defects in the conjugated backbone's chemical structure. The Maxwell-Wagner model and Debye relaxation have a major role in determining polarization loss. In organic conductive polymers, the charge transitions from  $\pi$  to  $\pi^*$  and  $n$  to  $\pi^*$  are crucial for conductive loss. The addition of heteroatoms and the use of either positive or negative doping in these materials simultaneously change the energy gap between the lowest unoccupied molecular orbital (LUMO) and the highest occupied molecular orbital (HOMO), which affects conductive and polarization losses, orbital orientations, and the arrangement of orbital occupancy by charges. Therefore, 1) oxidative, reductive, and elemental doping; 2) etching to produce defects; and 3) modifying the synthesis conditions to regulate morphology and conjugated lengths can all be used to modify the conductivity and polarization losses of organic conductive polymers as explained in the next sections, magnetic structures or the creation of secondary fields can be used to provide the missing permeability. The transmission line theory equation was used to evaluate the RL. Permeability, permittivity, and impedance matching are crucial components of microwave absorption (Zhou et al., 2022a). According to the Debye relaxation theory, electrical conductivity and polarization specifically, interfacial polarization and dipole polarization in the microwave spectrum are the main factors affecting permittivity in conjugated polymers. On the other hand, permeability is controlled by eddy currents, natural resonance, and exchange resonance (Yang et al., 2022a). Therefore, magnetic

loss is enhanced by increased saturation magnetization and decreased anisotropy. The eddy current loss increases with the eddy current curve's consistency. The permittivity of the conductive polymer is increased in organic polymers used as microwave-absorbing materials due to the simple electron transitions inside the conjugated structures. Therefore, the RL is modulated by the length of the polymer chains as well as the addition of heteroatoms as dopants. One important factor affecting the polarization loss and permittivity of microwave absorbers is the modification of morphology by adjusting heterogeneous interfaces (Zhou et al., 2022a). When the input and reflected waves are  $180^\circ$  out of phase and the matrix thickness is an odd multiple of  $\lambda/4$  of the propagating wave, the reflected waves from the reflector, which houses the absorbing media, can cancel out the wave coming from the absorber threshold. The key factor determining the absorber's capacity for energy conversion is the attenuation constant. To achieve a large reflection loss, there is a trade-off between impedance matching and the attenuation constant (Zhang et al., 2021c).

Electrical conductivity and polarization mechanisms are determined by the charge transitions in conjugated structures. The charge circuits can produce secondary fields, and the polarized structures can act as quasi-antennas. This leads to metamaterial characteristics and permeability that improve impedance matching. In Fig. 1, the possible mechanisms are shown. The features of metamaterials and quasi-antenna are discussed in the next section as viable approaches to creating conjugated carbon-based materials that absorb microwave radiation.

#### **Microwave-absorbing materials produced by Complex Materials**

Pure conjugated carbon and carbon-based compounds with heteroatoms included into their polymeric backbone make up organic conductive polymers. The high conductive and dielectric losses linked to SP<sup>2</sup> hybridization are explained by the simple charge transfers from  $\pi$  to  $\pi^*$  and from  $n$  to  $\pi^*$ . While the orbital orientation, guest electronegativity, defects, morphology, chain length, and non-bonding electrons on heteroatoms in other organic conductive polymers explain their electromagnetic responses, the morphology, defects, orbital orientation, and residual functional groups of pure carbon-based conductive polymers determine their microwave-absorbing capabilities.

Because of their superior electrical characteristics, conductive polymer structures have attracted interest in energy conversion and storage. Conjugated polymers' morphologies, orbital orientations, and chemical structures all have a big impact on how well they absorb microwaves. Elemental doping has been used in conjunction with magnetic and dielectric elements to enhance microwave-absorbing capabilities and achieve synergistic effects. This study looks at recent developments in conductive polymer structures made of heteroatom-containing organic polymers and conjugated carbon. In order to accomplish impedance matching, the materials' complex permittivity ( $\epsilon_r = \epsilon' - j\epsilon''$ ) and permeability ( $\mu_r = \mu' - j\mu''$ ) are used to assess their microwave-absorbing properties. Prime notation indicates storage capacity, while double-prime notation indicates an absorber's attenuation capacity. The reflection loss (RL) curves obtained from transmission line theory are used to examine the microwave absorption capabilities. An overview of conjugated carbon-based polymers and how their structures absorb microwaves is shown in Figure 1.

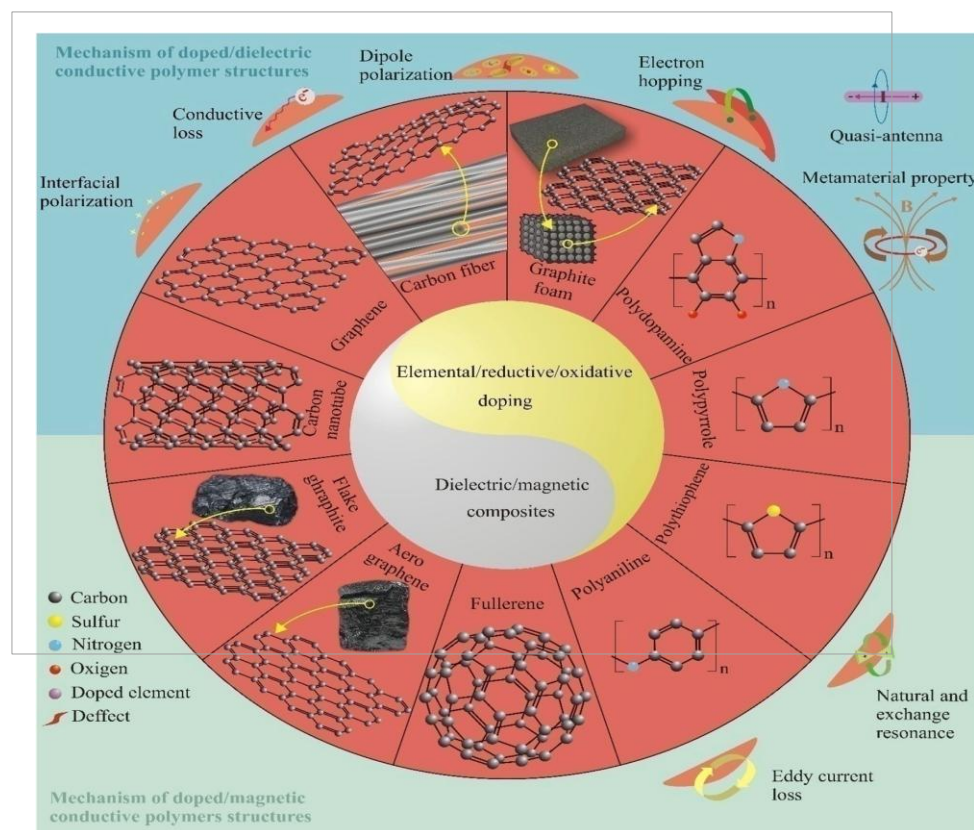


Fig. 1 Schematic representation of conductive polymer-based microwave-absorbing materials and their associated microwave-absorbing mechanisms

### Conjugated Polymers Incorporating Heteroatoms

Compared to natural polymers, synthetic polymers—such as polyesters and polyamides—offer a number of benefits, including easier large-scale synthesis, less batch-to-batch variability, and a wide range of modification options to achieve desired properties (Englert et al., 2018). While formulation parameters alone determine the final properties of materials, the chemistry of conductive polymers offers a wide range of synthetic methods that enable the integration of conductive elements into different media and the construction of complex structures. In addition to providing microwave-absorbing qualities, this capacity complies with environmental standards (Olmedo et al., 1995). These characteristics make polymers appealing candidates for tackling a number of issues in the field of microwave absorption.

Carbon nanospheres (CNS) were detected and supported on nanosilver-polydopamine (CNS-PDA/Ag) in a metamaterial composite (metacomposite) synthesized by Gu et al. The CNS-PDA/Ag metacomposite improved the conductive pathway, hence improving electrical conductivity, as seen by the impedance and optical band gap. The most noteworthy result of this investigation was the increased negative permittivity obtained from the combined secondary fields brought about by the unique structure created by the high-temperature annealing and hydrothermal processes.

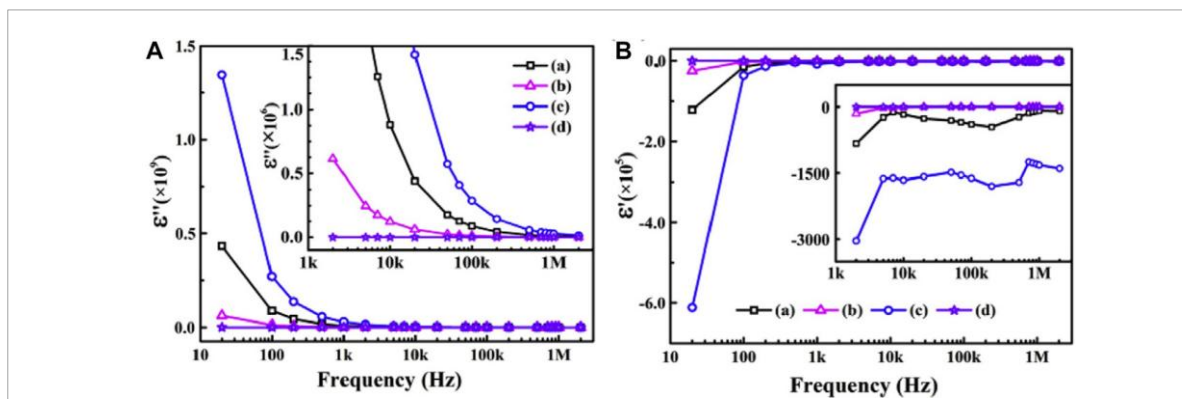


Fig. 2 Real part ( $\epsilon'$ ) and imaginary part ( $\epsilon''$ ) of permittivity for four components

While CNS showed negative permittivity, CNSP showed positive permittivity, as shown in Fig. 2. The improved graphitization of CNS, which increases electrical conductivity, is responsible for this discovery. By enriching the oxygen-containing functional groups on the CNS surface, PDA modification reduced the electrical conductivity of the CNS and controlled the conductivity in CNS-PDA. Ag nanoparticles are attached to the CNS-PDA surface in CNS-PDA/Ag. Conductivity is reduced and the CNS-PDA structure is enlarged when PDA is incorporated into the structure. Increased electrical conductivity causes the CNS and CNS-PDA/Ag to have negative permittivity. Ag nanoparticle deposition and CNSP carbonization improve charge routes. The Maxwell–Wagner–Sillars effect is responsible for the increased negative permittivity in CNS-PDA/Ag. Anisotropy in dielectric qualities and electrical conductivity is present in all three components—CNS, PDA, and Ag—and affects the final metacomposite's electrical properties (Gu et al., 2019; Lv et al., 2020).

A conjugated organic polymer with nitrogen as a heteroatom, polypyrrole (PPy), has attracted attention as a microwave absorber within the last ten years (Peymanfar et al., 2018). Qi et al. used conjugated conductive polymers to create a microwave absorber. Because of their persistent micropores and conjugated molecular fragments, conjugated microporous polymers, or CMPs, are being proposed. The process and precursors used to prepare CPTPB, CPTPA, and CPTB are shown in Fig. 3 (A). Using different ratios of pyrrole as a monomer, the authors evaluated the permittivities of CPTPB (TB/pyrrole 1:1), CPTPA (Tris (4-(PTPA)/pyrrole 1:3), and CPTB (PTB/pyrrole 1:3). As shown in Fig. 3 (C (a))–f, CPTPB had a higher permittivity than pure PPy. Lower conductivity and relaxation losses indicate that the permittivity decreased as the amount of pyrrole increased from CPTPB-3 to CPTPB-5. The increased permittivity brought about by replacing CPTPB and CPTB with CPTPA is confirmed in Figure 3. Carefully examined was the synergistic effect of  $\pi$ - $\pi$  stacking in carbon-based conjugated structures. Interfacial polarization is improved by this effect, which modifies heterogeneous interfaces (Jiao et al., 2020).



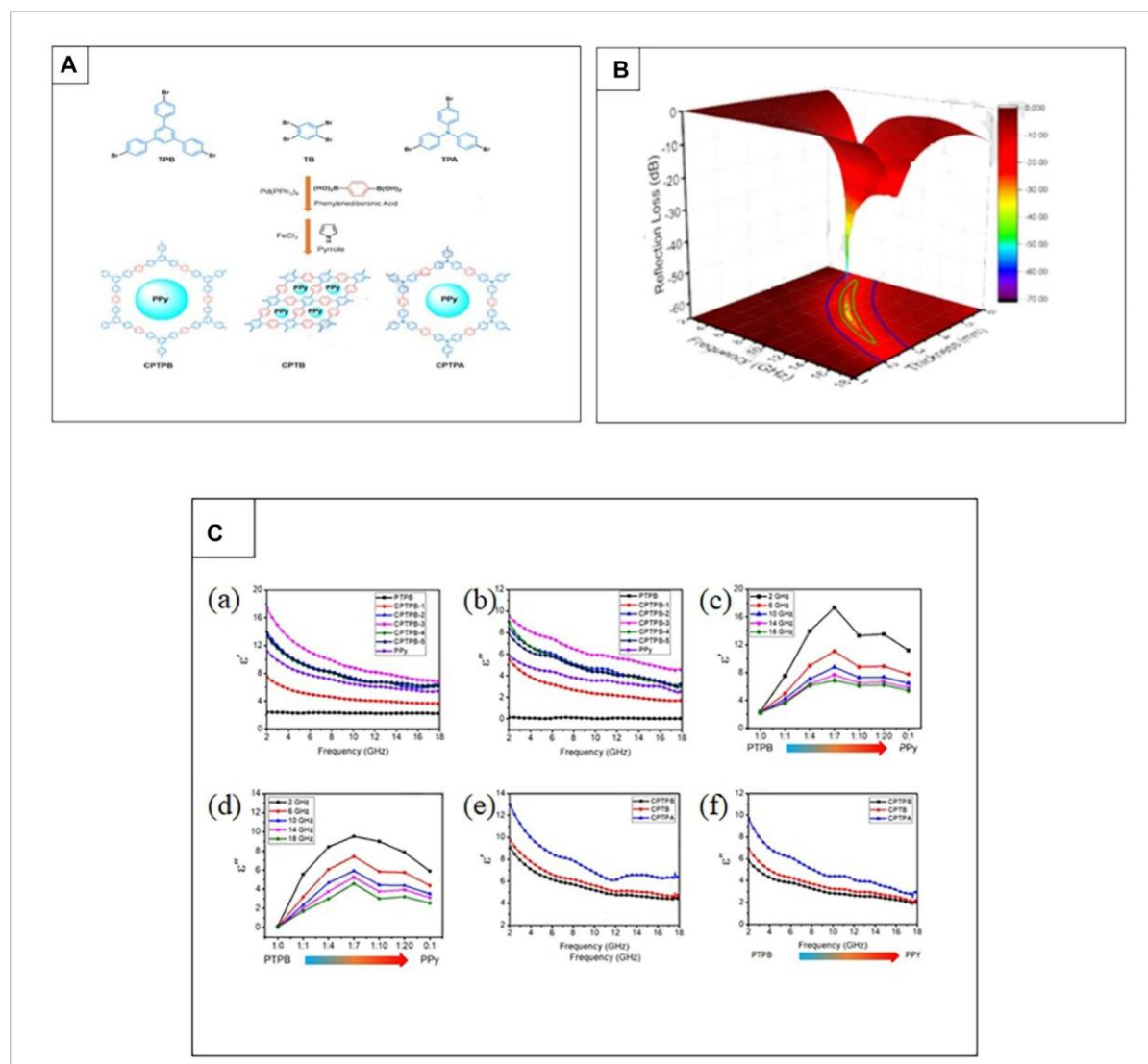


Fig. 3 Methodology for the synthesis of conductive CMPs

### Conductive polymers based on carbon and their microwave-absorbing configurations

Because of their remarkable microwave-absorbing capabilities, wide efficient bandwidth, and thin, light profile, carbon-based MAMs have attracted a lot of attention in recent decades, from basic theoretical research to experimental design and analysis (Zhao et al., 2016; Guan et al., 2021). Impedance mismatching causes the singular dielectric loss to have insufficient bandwidth in electromagnetic absorption (EMA), even if conjugated carbonaceous materials with different morphologies have considerable dielectric losses. Carbonaceous materials, such as carbon nanotubes (CNTs) (Munir, 2017), carbon fibers (CFs) (Wu et al., 2021), carbon spheres (Song et al., 2021), carbon micro-tubes (Peymanfar et al., 2021d), activated carbon (Mahmoodi et al., 2022), graphene (Wu et al., 2022), carbon net-like morphology (Peymanfar et al., 2021), and carbon black (Ibrahim et al., 2020) have all been bonded to carbonaceous materials. Due to the advent of synergistic loss processes in the customized composites and the customizable electromagnetic characteristics, this phenomenon can greatly increase the conjugated structures' microwave-absorbing capacity (Duan et al., 2018).

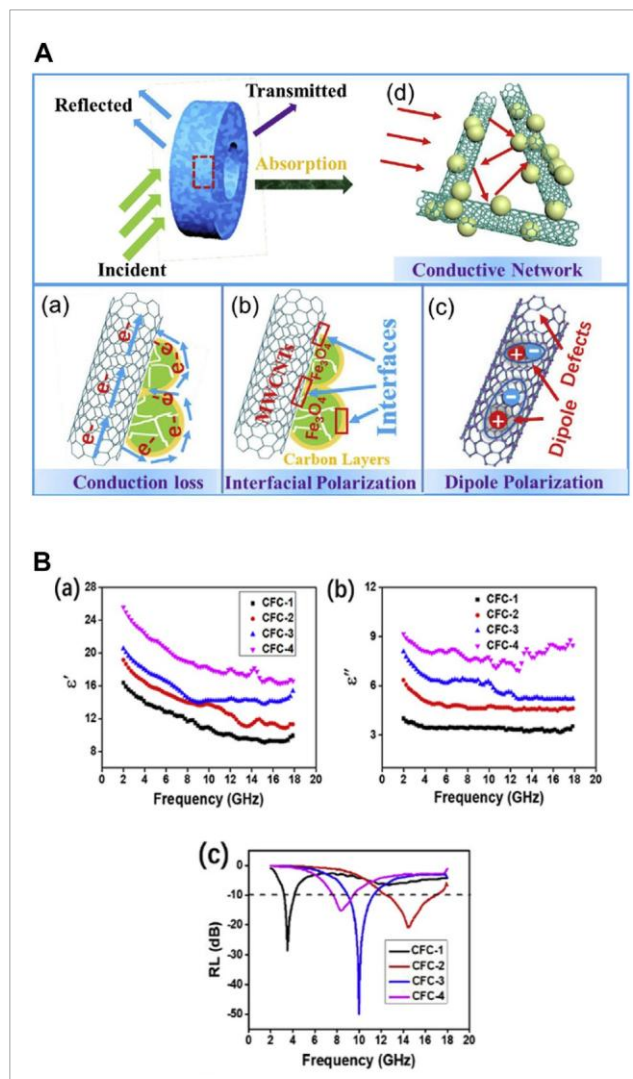


Fig. 4 Microwave absorption mechanisms associated with C@Fe<sub>2</sub>O<sub>3</sub>@MWCNT composites

Conjugated carbonaceous materials mixed with different designs have been reported to have remarkable microwave absorption capabilities in recent years. Two types of carbonaceous structures with improved conductive and dielectric qualities were included in the special conductive network that Che et al. created. Through a variety of processes, such as conductivity and relaxation losses, the ternary-phased C@Fe<sub>2</sub>O<sub>3</sub>@MWCNTs (CFC) produced thin, light, and highly effective microwave absorbers. The absorbent material's possible microwave-absorbing methods are depicted in Figure 4 (A).

As seen in Figure 4 (B (a)), a higher MWCNT content raises permittivity, suggesting a more efficient polarization loss process. A graph of RL in relation to the frequency of microwave absorbers with different MWCNT ratios is shown in Figure 4 (B (c)). At a thickness of 2.0 mm, the optimized absorber showed excellent MA performance with an RL of -49.9 dB. The multiphase component improved the interfacial polarization-promoting heterogeneous interfaces (Wang et al., 2019a).

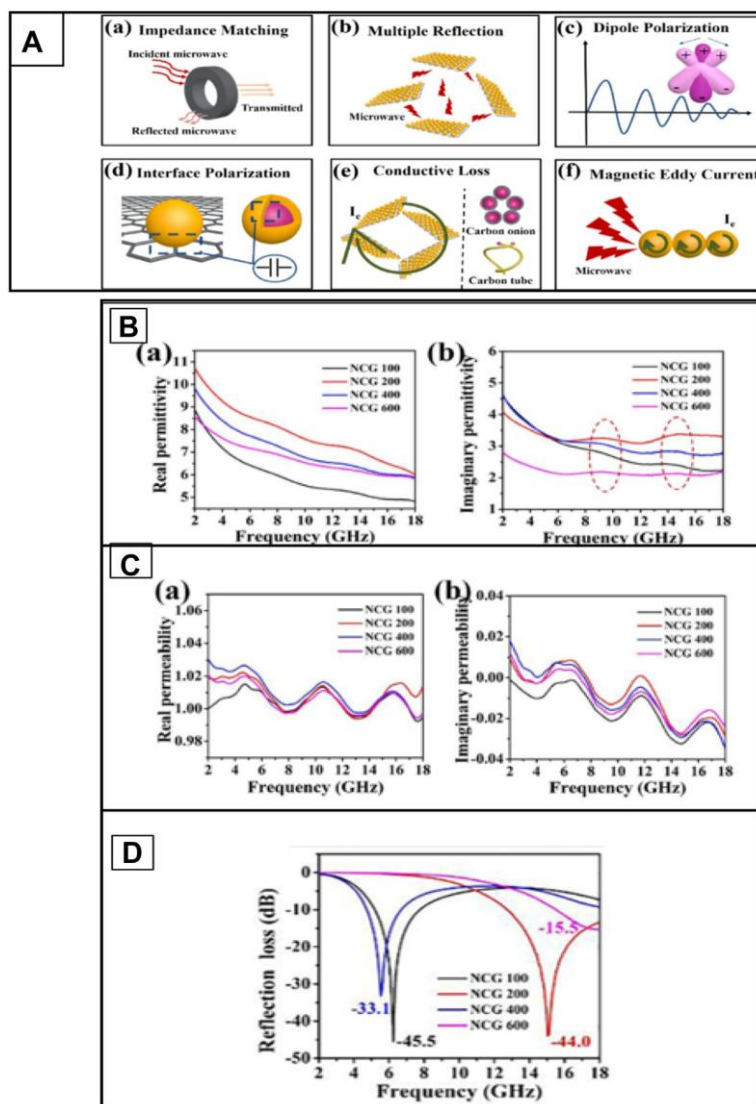


Fig. 5 Schematic representation of the principal microwave-absorbing mechanisms in the Ni@C/G and Ni/CNT/G absorbers

Wang et al. used two interesting ternary structures that were altered by atomic layer deposition (ALD) of NiO: Ni@carbon nano-onions and Ni/carbon nanotubes attached to graphene surfaces (Ni@C/G and Ni/CNT/G). Using a chemical vapour deposition technique, two different carbonaceous morphologies—carbon nano-onions and carbon nanotubes—were created on the graphene surface. In order to improve microwave absorption, the absorbers' unique morphologies gave them conductive networks, relaxation loss, natural and exchange resonance, eddy current loss, impedance matching, and a variety of reflections and dispersion. The results showed that, when compared to the related structures, the hybrid architectures have efficient microwave-absorbing properties with low filling ratios at low frequencies. The associated microwave-absorbing systems are summarized in Figure 5(A).

With different Ni ratios, the  $\epsilon'$  and  $\epsilon''$  of NCG are shown in Figure 5 (B (a,b)). By changing the concentration of nickel, one can modify the real and imaginary components of permittivity. The main causes of the permittivity



curves are polarization and conductive loss. Figures 3Ca and 3Cb show the complex permeability curves of NCG samples. The abnormalities are associated with exchange and natural resonances caused by Ni. At a thickness of 2.5 mm, NCG 100 demonstrated an effective bandwidth of 5.6 GHz and a peak reflection loss of  $-45.5$  dB at 6.2 GHz. The RLs of samples with different Ni concentrations are shown in Figure 3D, emphasizing how Ni amount affects microwave absorption (Xu et al., 2020).

Peymanfar et al. crumpled a nickel nanosheet and used it to encapsulate grape-like carbon microspheres (CMSs) in order to create a unique microwave-absorbing nanocomposite. They also looked at how the absorbing material affected the characteristics of microwave absorption. In the study that was presented, two-dimensional Ni nanostructures were first synthesized. CMSs made using the conventional hydrothermal method were then embellished with wrinkled nickel nanosheets using a combination of hydrothermal and ultrasonic methods. The distinct shape produced by the wrinkled structure enhanced microwave absorption by increasing polarization loss. Because of their conjugated topologies, CMSs have a large surface area, low density, and appropriate dielectric properties. CMSs and Ni together showed improved electromagnetic absorption in PS and PVDF matrices. According to the quarter wavelength concept, the CMSs' addition decreased the matching thickness by changing the complex permittivity and permeability. PVDF showed reduced relaxation loss and increased impedance matching and magnetic loss compared to the PS-produced sample. Significant magnetic characteristics and tight band gaps were present in all of the customized samples. The results showed that because of the wrinkled morphology of Ni and the used media, the constructed microwave-absorbing and shielding structures had high reflection loss, effective bandwidth, and shielding characteristics with little thickness. The absorbent matrix's possible microwave-absorbing mechanisms were depicted in Figure 4A. The Ni-containing composites showed a variety of notches due to their intrinsic and exchange resonances, as shown in Figure 4C. When PVDF was used in place of PS, the real and imaginary components of permittivity decreased while the imaginary component of permeability increased.

### Conclusion

An increasing amount of research on EMA in conjugated polymers has demonstrated that these conductive materials are excellent microwave absorbers because of their remarkable dielectric properties and lightweight designs, which enable a wide range of useful applications. This study examined various methods for forming organic polymer structures and clarified how doping and morphology affect conductive polymers' ability to absorb microwave radiation. Furthermore, the doped and composite structures were evaluated, and the mechanisms behind the microwave-absorbing capabilities of pure carbon-based absorbers and other conjugated organic polymers with heteroatoms were examined. Because of its remarkable electrical conductivity and quick electron transit, this class of materials has attracted a lot of interest for energy conversion and storage, as well as microwave absorption and shielding applications. The main factors affecting the microwave absorption of conjugated organic polymers are conductive and polarization losses; therefore, the analysis of morphology (wires, nanotubes, fibers, 2D structures, fabric, etc.) and orbital orientations that facilitate charge transitions is essential for the effectiveness of microwave absorption. Strong dielectric characteristics reduce effective bandwidth, microwave attenuation, and incident wave transmission into the absorbing medium by affecting impedance matching. As a result, these materials use magnetic components to increase impedance matching, permeability, and microwave absorption, which makes testing more difficult. By modifying the energy band gap and charge accumulation in the highest occupied molecular orbital (HOMO), doping—whether elemental, oxidative, or reductive—helps control polarization and conductive losses. Dielectric materials with characteristic morphologies are found to have metamaterial and quasi-antenna mechanisms. Secondary fields can be generated via charge circuits in conjugated structures and conductive networks; polarized structures with particular morphologies can provide quasi-antenna topologies that improve permeability and optimize impedance matching. Importantly, the doped atoms behave as centers of polarization, where higher electronegativity draws electron clouds, promoting charge accumulation,

promoting dipole polarization, and displaying quasi-antenna properties. However, the actual use of several conjugated organic polymers is limited due to their complex production methods. Pyrolyzed biomass-derived materials have been widely used as readily available and reasonably priced precursors for the production of microwave-absorbing materials in order to get around this problem. In order to improve the microwave-absorbing efficiency of useful microwave refiners, this work explores the mechanisms of metamaterials and quasi-antennas and clarifies the design of conjugated organic polymers with unique shape. Importantly, the presented results demonstrated that doping is a useful technique for improving conjugated structures' ability to absorb microwave radiation.

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