Electromagnetic Shielding Materials: A Survey

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Abstract

Electromagnetic shielding is a crucial technique employed to mitigate electromagnetic interference (EMI) that can impair electronic device performance. This survey paper reviews various materials used for EMI shielding, including polymer foams, carbon-based foams, metal-based foams, dielectric materials, and radar absorbing materials. The paper highlights the demand for lightweight, flexible, and effective shielding solutions driven by advancements in technology such as 5G communications. It discusses the mechanisms through which these materials operate, emphasizing the roles of reflection, absorption, and transmission. The survey also explores the integration of advanced materials like graphene and MXenes, which enhance shielding effectiveness through improved electrical conductivity and thermal stability. The comparative analysis section evaluates the trade-offs between optical transmittance and EMI shielding, essential for applications requiring transparency. Recent advancements, including the development of reconfigurable intelligent surfaces and innovative fabrication techniques like 3D printing, are considered for their potential to enhance shielding performance. Future research directions are suggested, focusing on optimizing material properties, exploring new configurations, and addressing environmental concerns associated with traditional materials. The survey concludes by underscoring the importance of innovative solutions in safeguarding electronic systems against EMI, ensuring their reliability and functionality in complex electromagnetic environments.

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1 Introduction

1.1 Concept and Importance of Electromagnetic Shielding

Electromagnetic shielding is essential for reducing electromagnetic interference (EMI), which can adversely affect electronic device performance. The rise of 5G communication technologies and the increasing number of electronic devices amplify the need for effective EMI shielding materials, particularly due to potential health risks associated with electromagnetic radiation [1]. Traditional metal-based shielding materials, while effective, are often hindered by high density and corrosion susceptibility, prompting the search for alternative materials with superior performance characteristics [2].

The development of flexible, lightweight materials is vital for practical applications requiring efficient EMI shielding solutions [3]. Reconfigurable intelligent surfaces (RISs), while promising for wireless communication systems, pose challenges by reflecting unwanted signals and contributing to EMI [4]. This highlights the necessity for advanced materials capable of effectively shielding against EMI while meeting the demands of contemporary communication systems.

In high-frequency applications, understanding the magnetic permeability spectrum of materials is critical for designing components like radar absorbing materials and high-frequency inductors [5]. Furthermore, the integration of novel detection systems, such as those for bioparticle monitoring, emphasizes the need to enhance sensitivity and specificity to counteract EMI effects [6]. As technological advancements progress, the strategic implementation of electromagnetic shielding remains

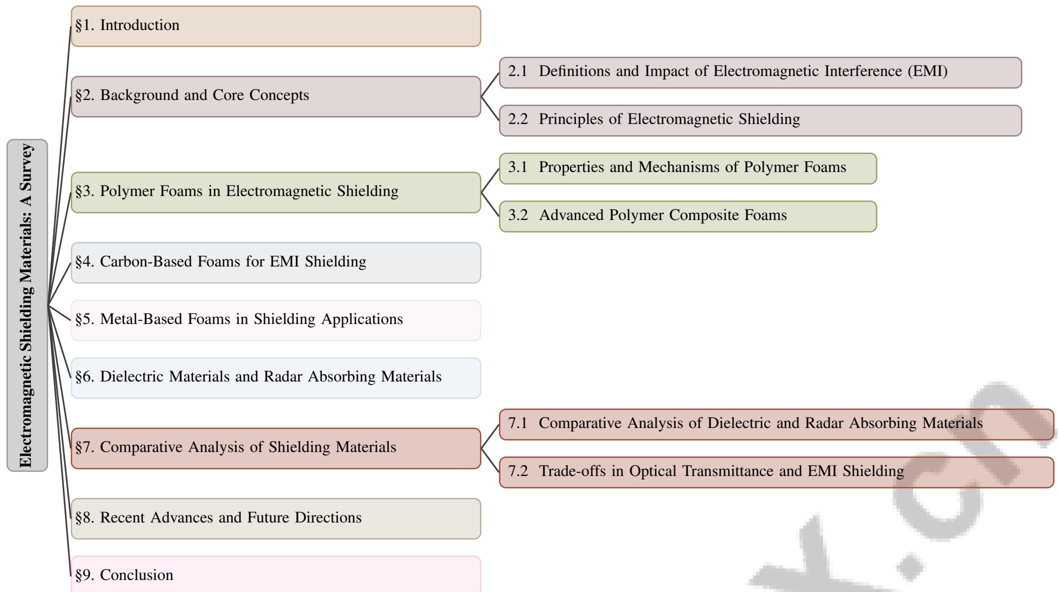

Figure 1: chapter structure

vital across various sectors, including healthcare and information technology, ensuring the reliability and safety of electronic systems in complex electromagnetic environments.

1.2 Structure of the Survey

This survey is systematically organized to provide a thorough examination of electromagnetic shielding materials, categorizing them based on their electromagnetic properties and application contexts as outlined by Celozzi et al. [7]. The introduction establishes the significance of electromagnetic shielding in mitigating EMI within modern technological environments. Section 2 delves into the background and core concepts, defining and exploring the mechanisms through which shielding materials operate.

Section 3 focuses on polymer foams, detailing their properties, advantages, and mechanisms that contribute to effective EMI shielding, alongside an exploration of advanced polymer composite foams [8]. Section 4 examines carbon-based foams, emphasizing their conductivity and lightweight nature, which are crucial for EMI applications [9]. The discussion in Section 5 extends to metal-based foams, analyzing their metallic properties and comparative performance with other materials.

Section 6 investigates dielectric materials and radar absorbing materials, elucidating their roles in EMI reduction via absorption and reflection mechanisms. The survey progresses to a comparative analysis in Section 7, evaluating the effectiveness, cost, and application scenarios of the discussed materials, while addressing trade-offs such as optical transmittance versus EMI shielding effectiveness [10].

Recent advancements and future directions are presented in Section 8, focusing on emerging technologies and potential research avenues that promise to enhance the field of electromagnetic shielding materials. Finally, Section 9 synthesizes key insights and highlights the ongoing importance of innovative shielding solutions in protecting electronic systems against EMI [1].The following sections are organized as shown in Figure 1.

2 Background and Core Concepts

2.1 Definitions and Impact of Electromagnetic Interference (EMI)

Electromagnetic interference (EMI) encompasses disturbances from external electromagnetic sources that degrade electronic circuit performance. Such interference is particularly detrimental in sensitive applications like radio telescopes, where radio frequency interference (RFI) impairs detection [11].

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The integration of millimeter-wave technologies in wireless communication amplifies EMI challenges, necessitating robust shielding solutions [12].

The repercussions of EMI span diverse technological fields. In high-temperature electronic devices, inadequate EMI shielding exacerbates thermal management issues, affecting performance and longevity [13]. Effective shielding materials must balance electrical conductivity and dielectric properties to maintain device efficiency while minimizing interference [9]. The dielectric response, especially in composites with metal or superconducting particles, is crucial for shielding efficacy [14].

In wireless systems, EMI adversely affects channel estimation in RIS-aided cell-free massive MIMO systems, where phase errors degrade performance [15]. RIS-induced signal reflections introduce local interference, necessitating advanced EMI cancellation to bolster communication reliability [4]. Misinterpretations of EMI shielding effectiveness (EMI SE) can lead to incorrect material evaluations, highlighting the need for precise definitions and assessments [16].

The advancement of lightweight, flexible EMI shielding materials is vital for wearable devices, ensuring impact resistance and thermal dissipation to prevent short circuits and ensure safe operation [2]. These material innovations are crucial to counteract the varied effects of EMI, ensuring reliable electronic system operation in complex electromagnetic environments.

2.2 Principles of Electromagnetic Shielding

Electromagnetic shielding involves reflection, absorption, and transmission processes, reliant on the material's electrical, magnetic, and dielectric properties. Conductive materials, particularly metals, effectively reflect waves, mitigating EMI in sensitive settings. Designing shielding enclosures and implementing power line filters and optical fibers are essential strategies in actuator systems [17]. Balancing reflection and absorption, especially in the GHz range, requires innovative material design. Conductive metasurfaces like Split Ring Resonators (SRRs), created via 3D printing, enhance shielding by promoting wave reflection and absorption [3].

Dielectric materials are pivotal in stealth applications, absorbing waves and converting energy to heat. The surface integral formulation offers an efficient analysis of layered dielectric structures, reducing computational costs while maintaining prediction accuracy [18]. Stable algorithms using symmetric positive definite matrices improve simulation accuracy in complex dielectric environments [19].

Integrating reflection and absorption is crucial for effective shielding, as seen in RIS-assisted uplink transmissions in cell-free massive MIMO systems, where EMI and spatial correlations must be considered [15]. Innovative EMI cancellation schemes, adjusting RIS phase shifts, enhance the signal-to-interference-plus-noise ratio (SINR) at receivers, underscoring the need for dynamic adaptability in modern shielding solutions [4].

Advanced characterization methods are vital for accurately modeling electromagnetic properties, particularly inhomogeneities and high conductivity, crucial for precise property extraction [20]. Calculating Casimir forces in inhomogeneous media involves defining energy variations and extracting finite terms from energy and stress tensors, illustrating complex electromagnetic interactions [21].

Developing highly flexible EMI shielding materials is challenging due to mechanical property compromises from conductive fillers [22]. However, strategic material property manipulation allows control over wave interactions, ensuring electronic system reliability and safety. Theoretical perspectives involve using homogenization and matched asymptotic expansions for electromagnetic scattering analysis, as shown in deriving effective interface conditions for scattering by thin periodic layers of perfectly-conducting obstacles [23].

Addressing scalability and performance challenges in electromagnetic shielding involves using materials with high thermal conductivity and unique electromagnetic properties, like graphene, which enable efficient heat dissipation and EMI shielding. Advancements in high-performance, lightweight, flexible, multifunctional materials are essential to address environmental concerns related to composition and enhance shielding effectiveness [1].

In recent years, the application of polymer foams in electromagnetic shielding has garnered significant attention due to their unique properties and mechanisms. As illustrated in Figure 2, this figure presents a hierarchical categorization of polymer foams, emphasizing their structural attributes and

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the enhancements they provide in shielding efficacy. Furthermore, it highlights the versatility of these materials across various applications, showcasing innovative materials and techniques employed in the development of advanced polymer composite foams. This comprehensive overview not only underscores the importance of polymer foams in modern engineering but also sets the stage for further exploration into their potential applications and improvements in electromagnetic interference (EMI) shielding.

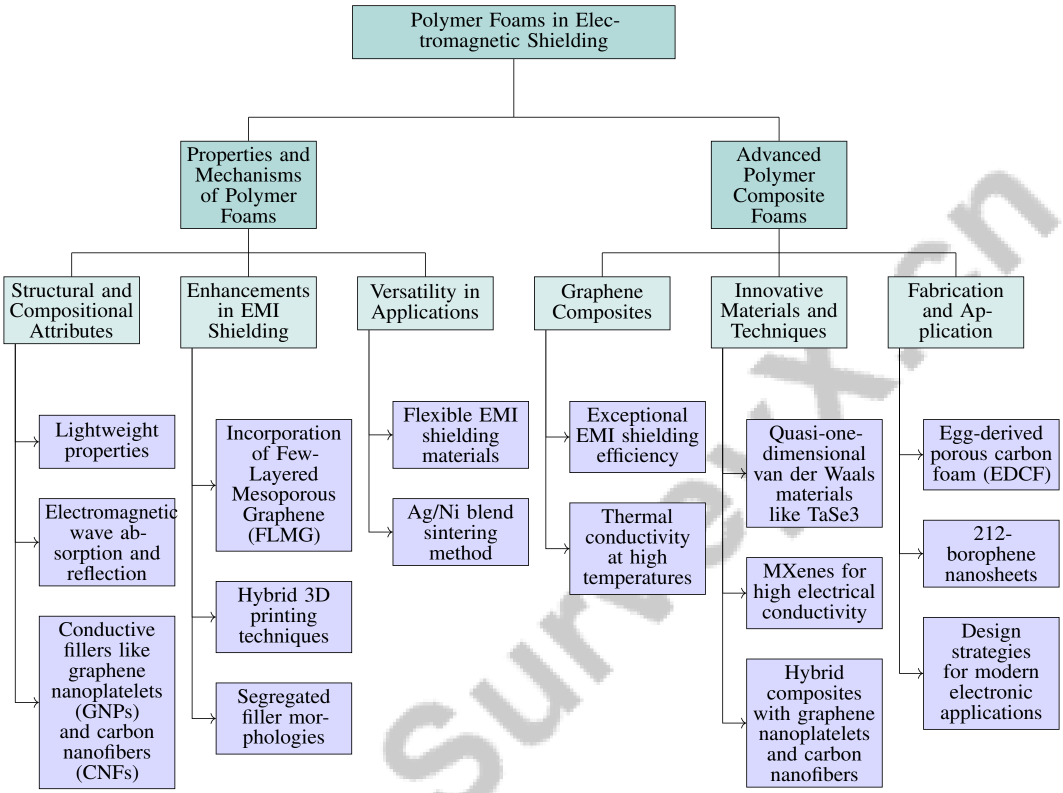

Figure 2: This figure illustrates the hierarchical categorization of polymer foams in electromagnetic shielding, highlighting their properties, mechanisms, and advanced composite forms. It demonstrates the structural attributes, enhancements in shielding, and versatility in applications of polymer foams, as well as the innovative materials and techniques used in advanced polymer composite foams.

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3 Polymer Foams in Electromagnetic Shielding

3.1 Properties and Mechanisms of Polymer Foams

Polymer foams are integral to electromagnetic interference (EMI) shielding, attributed to their structural and compositional attributes. Their cellular architecture ensures lightweight properties while facilitating electromagnetic wave absorption and reflection. Incorporating conductive fillers such as graphene nanoplatelets (GNPs) and carbon nanofibers (CNFs) into polymer matrices enhances EMI shielding by improving thermal stability, electrical conductivity, and mechanical properties, as demonstrated in polyhydroxyalkanoate (PHA) biopolymers [24]. The addition of Few-Layered Mesoporous Graphene (FLMG) with amorphous magnetic materials further augments the shielding effectiveness by enhancing electrical conductivity without compromising the foam's lightweight nature [25].

Hybrid 3D printing techniques enable the creation of metamaterials that optimize shielding by achieving narrowband transmission, broadband absorption, and perfect reflection [26]. The cellular structure of polymer foams increases surface area for electromagnetic interaction, thereby improving shielding effectiveness. Using segregated filler morphologies like carbon nanotubes and boron nitride enhances conductive pathways, boosting both EMI shielding and thermal management [10]. The

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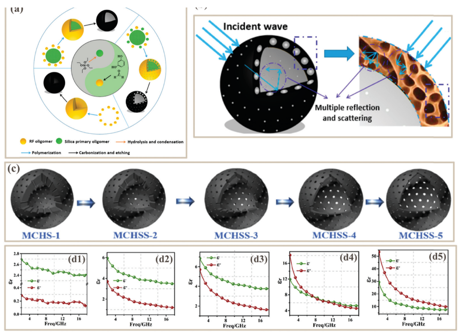
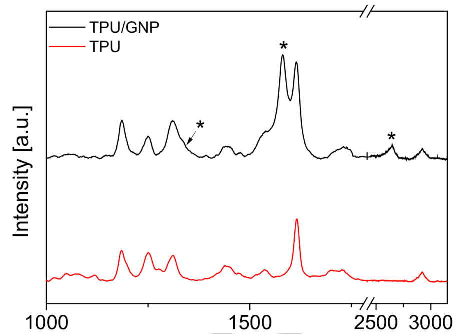
arrangement of conductive fillers in periodic layers significantly influences shielding behavior by affecting electromagnetic wave interaction pathways [23].

Polymer foams offer high flexibility and lightweight construction, critical for modern electronics. Flexible EMI shielding materials, such as those developed via the Ag/Ni blend sintering method, result in films with enhanced electrical conductivity and improved electromagnetic shielding and mechanical properties [2]. These advancements demonstrate the versatility of polymer foams in developing advanced EMI shielding solutions suitable for lightweight, electrically insulating, and flexible films with high shielding efficiency at low filler loading fractions.



(a) Multifunctional Hollow Sphere with Enhanced Dielectric Properties[27]



(b) The image shows two X-ray diffraction (XRD) patterns of TPU/GNP and TPU materials.[28]

Figure 3: Examples of Properties and Mechanisms of Polymer Foams

Figure 4 illustrates the categorization of polymer foams in electromagnetic shielding, highlighting the role of conductive fillers, advanced manufacturing techniques, and structural benefits that enhance shielding effectiveness. The first example shows a multifunctional hollow sphere with enhanced dielectric properties, achieved via polymerization, carbonization, and etching processes. This sphere, comprising RF oligomer, silica primary oligomer, and hydrolysis and condensation, emphasizes multiple reflections and scattering, crucial for effective EMI shielding. The second example presents X-ray diffraction (XRD) patterns of thermoplastic polyurethane (TPU) combined with graphene nanoplatelets (GNP), revealing the complex structural characteristics contributing to superior electromagnetic shielding performance compared to standard TPU [27, 28].

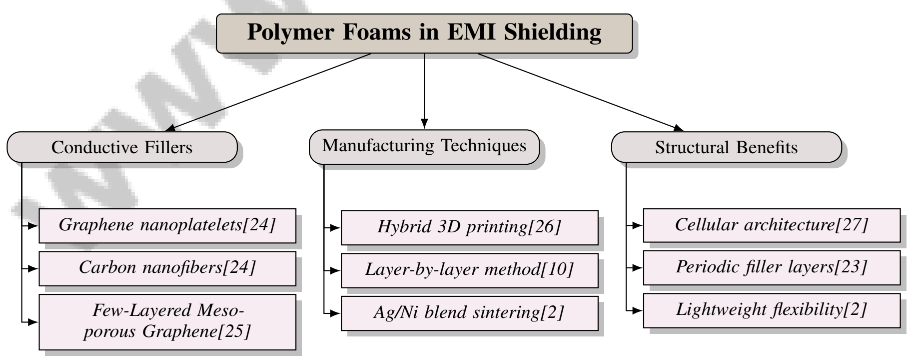


Figure 4: This figure illustrates the categorization of polymer foams in electromagnetic interference (EMI) shielding, highlighting the role of conductive fillers, advanced manufacturing techniques, and structural benefits that enhance shielding effectiveness.

3.2 Advanced Polymer Composite Foams

Advanced polymer composite foams represent a significant advancement in EMI shielding, combining mechanical flexibility with superior electromagnetic properties. Graphene composites exhibit exceptional EMI shielding efficiency and thermal conductivity at temperatures exceeding 500 K,

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outperforming traditional materials [13]. This resilience is vital for applications in harsh environments requiring effective EMI shielding and thermal management.

Incorporating quasi-one-dimensional van der Waals materials, such as tantalum triselenide (TaSe3), into polymer matrices enables the development of polarization-sensitive EMI shielding materials. These composites use aligned metallic fillers to selectively attenuate electromagnetic waves based on polarization, offering tailored EMI protection [29]. The exploration of MXenes, a class of two-dimensional transition metal carbides and nitrides, highlights their potential in EMI applications due to high electrical conductivity and tunable surface chemistry [30].

Hybrid composites with graphene nanoplatelets and carbon nanofibers in a wax emulsion demonstrate enhanced conductivity and mechanical properties, showcasing their versatility in meeting diverse EMI application requirements [31]. Additionally, graphene-thermoplastic polyurethane (TPU) coatings exhibit low electrical resistance and durability after extensive mechanical cycling, making them suitable for stretchable electronics and EMI shielding [32].

Innovative fabrication techniques, such as using egg-derived porous carbon foam (EDCF), control pore volume and surface area, optimizing electromagnetic wave absorption [33]. The strategic incorporation of quasi-1D TaSe3 fillers at low concentrations into polymer matrices results in electrically insulating, flexible films providing significant EMI shielding [34]. Integrating 212-borophene nanosheets into polymer matrices harmonizes material quantity with shielding effectiveness, achieving high performance with minimal material usage [35].

Recent advancements in advanced polymer composite foams underscore their potential to meet modern electronic application demands, particularly in EMI shielding. These materials, characterized by lightweight, flexible, and multifunctional properties, are ideal for mitigating electromagnetic radiation effectively. As electronic device proliferation raises EMI concerns, the demand for high-performance shielding solutions becomes critical. Recent research illustrates design strategies and mechanisms enhancing these foams' functionality and flexibility, positioning them as promising candidates for next-generation electronic devices requiring reliable and sustainable EMI protection [36, 1].

4 Carbon-Based Foams for EMI Shielding

4.1 Composition and Microstructure of Carbon-Based Foams

Carbon-based foams are distinguished by their superior EMI shielding properties, attributed to their unique composition and microstructure. The porous architecture significantly enhances absorption by facilitating multiple reflections and scattering of electromagnetic waves [27]. This feature is particularly advantageous for microwave absorption applications, increasing the interaction time of electromagnetic waves with the material to improve shielding effectiveness. Figure 5 illustrates the key components and techniques in carbon-based foams that enhance electromagnetic interference (EMI) shielding, focusing on porous architecture, graphene enhancement, and aligned pore structures.

The incorporation of graphene and other carbon allotropes into the foam matrix further enhances EMI shielding. Techniques like layer-by-layer coating with graphene and polyelectrolytes markedly improve shielding effectiveness, with performance directly related to the number of graphene layers [37]. This method allows precise control over electrical conductivity and the formation of conductive networks within the foam, crucial for electromagnetic wave attenuation.

Aligned pore structures, especially in biomass-derived composites, enhance EMI shielding by promoting multiple reflections and improving wave absorption [36]. Strategic design of these pores and interfaces, such as those between lignin and reduced graphene oxide (RGO), aids in trapping and dissipating electromagnetic energy, increasing shielding efficiency.

Advancements in the metallization of carbon fiber reinforced polymers (CFRPs) using cold spray methods enhance the adhesion and performance of carbon-based foams without compromising the epoxy matrix [38]. This technique deposits metal coatings that improve conductive pathways, boosting EMI shielding properties.

Studies on equivalent dielectric constant frequency (EDCF) samples with varying pore volumes and surface areas provide insights into optimizing electromagnetic wave absorption across different frequency bands [33]. These findings highlight the importance of tailoring microstructural character-

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istics to achieve desired shielding properties, showcasing the versatility and potential of carbon-based foams in advanced EMI shielding applications.

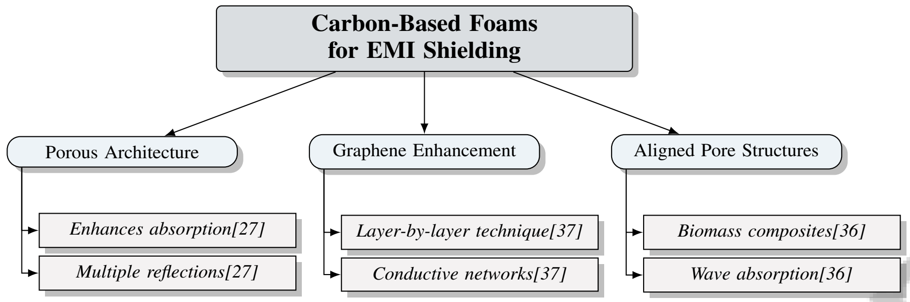

Figure 5: This figure illustrates the key components and techniques in carbon-based foams that enhance electromagnetic interference (EMI) shielding, focusing on porous architecture, graphene enhancement, and aligned pore structures.

4.2 Unique Properties and Performance Enhancements

Carbon-based foams offer unique properties that enhance EMI shielding, primarily due to their structural and compositional characteristics. A key development challenge is balancing low density, strong absorption, and effective impedance matching while addressing environmental stability and production costs [27]. The porous structure facilitates multiple reflections and scattering of electromagnetic waves, enhancing absorption and overall shielding effectiveness.

The integration of thermoplastic polyurethane (TPU) with graphene nanoplatelets (GNPs) has led to significant advancements. TPU/GNP microcellular foams achieve EMI shielding efficiencies of 16-18 dB with only 1 wt

Carbon-based foams provide high mechanical reinforcement and exceptional electrical conductivity, contributing to superior EMI shielding performance. These properties are achieved with lower weight and thickness than traditional materials, emphasizing the advantages of carbon-based foams in lightweight and compact applications [39]. The strategic design enhances both mechanical and electromagnetic properties, making them suitable for advanced technological applications.

Recent research focuses on optimizing the microstructure of carbon-based foams to enhance performance. By tailoring pore architecture and incorporating advanced materials, researchers improve impedance matching and absorption capabilities, maximizing shielding effectiveness across a wide frequency range. Biomass-based carbon foams, particularly those derived from lignin and doped with reduced graphene oxide, demonstrate exceptional performance as lightweight, robust, and sustainable materials for EMI shielding. These foams achieve impressive shielding effectiveness of 28.5 to 70.5 dB at low densities, with a normalized surface specific shielding effectiveness as high as 28,750 dB·cm²/g, surpassing many conventional materials. Their honeycomb-like structure and aligned pore architecture enhance electrical conductivity and mechanical properties, offering a promising solution for mitigating electromagnetic pollution in modern electronic applications [36, 1].

As illustrated in Figure 6, carbon-based foams are promising for EMI shielding due to their unique properties and performance enhancements. Advanced materials, including various MXene structures and doped SnO2 nanoparticles, highlight their potential in improving EMI shielding capabilities. A comparative analysis of different MXene structures, including mono-transition metal MXenes and ordered double-transition metal MXenes, showcases the diversity and adaptability of these materials. Each structure is meticulously illustrated with diagrams and photographs, emphasizing a tailored approach to optimizing EMI shielding. The characterization of doped SnO2 nanoparticles through XRD patterns and Raman spectra provides a comprehensive understanding of their structural and compositional properties, collectively underscoring the innovative strides in utilizing carbon-based foams and related materials for superior EMI shielding performance [30, 40].

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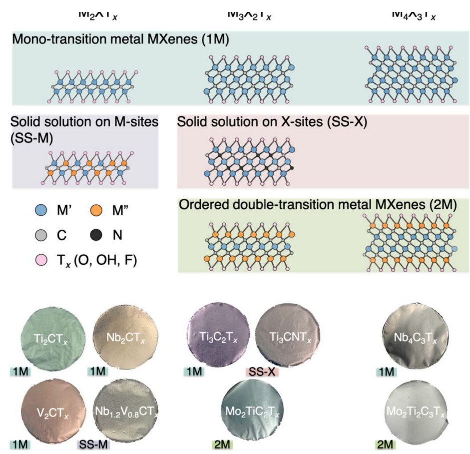
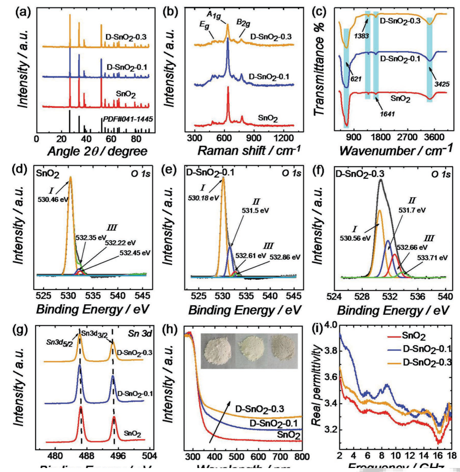


(a) Various MXene Structures and Their Corresponding Materials[30]



(b) Characterization of Doped SnO2 Nanoparticles[40]

Figure 6: Examples of Unique Properties and Performance Enhancements

5 Metal-Based Foams in Shielding Applications

5.1 Advantages of Metal-Based Foams

Metal-based foams offer notable advantages for electromagnetic interference (EMI) shielding due to their unique material properties and structural configurations. Their robust shielding capability coupled with lightweight construction makes them ideal for weight-sensitive applications [41]. The high surface area of these foams enhances their ability to reflect and absorb electromagnetic waves, thereby improving shielding effectiveness. Periodic structures within metal-based foams, such as wire mesh, can further enhance shielding by optimizing the topology for comprehensive EMI protection [23]. This structural advantage, combined with the inherent conductivity of metals, facilitates electromagnetic wave reflection, reducing EMI penetration into sensitive electronic systems.

Metal-based foams can also be engineered for dual functionality, such as asymmetric transmission and shielding, enhancing their versatility across various applications. This intelligent design allows for selective EMI blocking while maintaining mechanical strength and thermal conductivity [41]. Combining metal-based foams with advanced materials, like Few-Layered Mesoporous Graphene (FLMG) and amorphous magnetic materials, significantly amplifies shielding performance, surpassing traditional metal-based solutions [25]. Detailed analyses of EMI effects on electronic transport systems reveal that metal-based foams enhance the safety and functionality of these systems, underscoring their relevance in modern electronic applications [42].

The effective absorption and reflection properties of metal-based foams make them highly effective for mitigating EMI challenges across technological domains such as telecommunications, consumer electronics, and industrial applications [16, 43, 8, 7, 1].

5.2 Emerging Technologies in Metal-Based Shielding

Innovative fabrication techniques and multifunctional capabilities are transforming metal-based shielding materials. The blade coating method, which involves drop casting a polymer-filler solution onto a substrate and using a blade to spread the mixture, aligns quasi-one-dimensional fillers, enhancing the anisotropic electromagnetic properties of the composite [29]. This alignment is crucial for optimizing directional shielding performance, making it promising for tailored EMI mitigation applications.

As illustrated in Figure 7, which depicts the hierarchical structure of emerging technologies in metal-based shielding, the advancements in blade coating and Ag/Ni blend sintering methods are prominently highlighted. This figure emphasizes key fabrication techniques, material innovations,

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and application areas, showcasing the integration of these methods in the context of 5G technologies and optical systems.

Metal mesh-based materials provide effective EMI shielding while maintaining high optical transparency, overcoming existing limitations by balancing shielding effectiveness and optical clarity, particularly beneficial for infrared-transparent systems [44]. This capability to preserve transparency without compromising shielding performance opens new avenues for integrating these materials into advanced optical and electronic devices.

The emergence of terahertz reconfigurable multifunctional metamaterials introduces a transformative approach to metal-based shielding. These materials can switch between multiple functionalities easily, offering rapid fabrication and reduced costs compared to traditional methods [26]. Their versatility allows adaptation to various electromagnetic environments, enhancing applicability across diverse technological domains.

The development of advanced metal-based shielding materials highlights significant innovations that enhance EMI shielding performance while incorporating multifunctional capabilities, addressing the urgent requirements of modern electronic devices, especially in the context of emerging 5G technologies. Materials such as flexible composites, including ultrathin Ni/Ag films and graphene-based structures, demonstrate exceptional shielding effectiveness while maintaining high flexibility and ease of production. This combination of properties positions them as promising solutions for next-generation applications in electronic and optical systems, improving reliability and versatility in protecting sensitive components from electromagnetic radiation and interference [25, 22, 1].

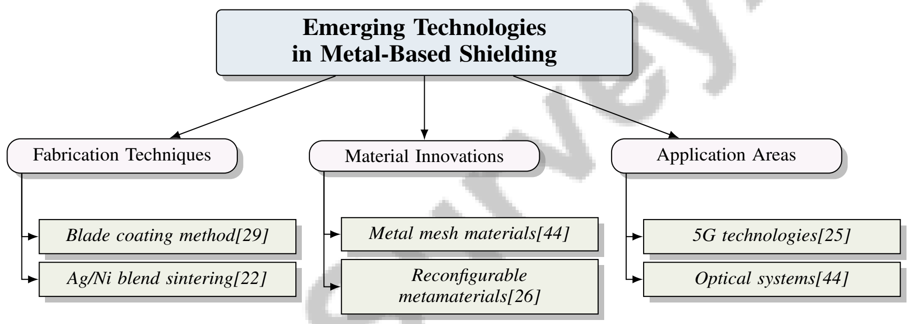

Figure 7: This figure illustrates the hierarchical structure of emerging technologies in metal-based shielding, highlighting key fabrication techniques, material innovations, and application areas. It emphasizes the advancements in blade coating and Ag/Ni blend sintering methods, innovations in metal mesh and reconfigurable metamaterials, and their applicability in 5G technologies and optical systems.

6 Dielectric Materials and Radar Absorbing Materials

6.1 Mechanisms of Dielectric Materials in EMI Shielding

Dielectric materials play a crucial role in electromagnetic interference (EMI) shielding by absorbing and dissipating electromagnetic energy through dielectric loss processes. Upon exposure to an electromagnetic field, these materials undergo polarization, causing dipole moments to align with the field and convert electromagnetic energy into heat [45]. The shielding efficacy of dielectric materials is largely influenced by their complex permittivity, comprising real and imaginary components; the former relates to energy storage, while the latter, known as the dielectric loss factor, pertains to energy dissipation [46].

Advanced theoretical frameworks, such as path integral quantization of the electromagnetic gauge field, provide a systematic understanding of the interaction between fluctuating electromagnetic fields and dielectric materials, elucidating energy dissipation mechanisms [47]. Additionally, homogenization formalisms for particulate composites classify materials with both amplification and dissipation, enhancing our comprehension of dielectric behavior in EMI shielding [46].

The pursuit of dielectric materials with high dielectric constants and large band gaps is essential for optimizing EMI shielding while minimizing computational costs associated with ab-initio calculations

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[48]. Techniques like the meta-dome method improve impedance matching between metasurfaces and free space, reducing reflection and maximizing absorption [49]. These advancements highlight the potential of dielectric materials in providing effective EMI shielding through tailored properties and innovative engineering.

6.2 Radar Absorbing Materials and Their Mechanisms

Radar absorbing materials (RAM) are integral to EMI shielding, attenuating electromagnetic waves via mechanisms such as dielectric polarization and conduction loss. As illustrated in Figure 8, these primary mechanisms are complemented by characterization tools and innovative approaches in the study of RAM. Notably, Point Defect Engineering exemplifies a method that balances conduction loss with dielectric polarization, enhancing the permittivity of dielectric materials and improving RAM absorption efficiency, crucial for minimizing radar cross-sections [40].

RAM characterization is advanced by tools like the Terascan 1550 system, which measures absorber reflectance over a wide frequency range and various angles, allowing comprehensive performance assessments in diverse electromagnetic environments [50]. The microwave absorption properties of RAM are significantly affected by their magnetic permeability and dielectric permittivity, with material composition playing a critical role in effective EMI shielding [51]. Factors such as pore volume and specific surface area also significantly influence electromagnetic wave absorption [33].

Theoretical insights into RAM magnetic properties, derived from the generalized integral of Noek's law, provide robust estimates even in the presence of skin effects, proving invaluable for microwave measurements and material design [5]. The phenomenon of 'diaelectricity' in certain nanoparticle aggregates suggests RAM may exhibit unique dielectric properties under specific conditions, expanding their applicability in EMI shielding [45].

Understanding RAM mechanisms is essential for effective EMI shielding. Recent advancements in material characterization and theoretical frameworks are leading to more efficient solutions for electromagnetic wave attenuation. Research emphasizes the potential of composite materials that enhance shielding performance and the integration of RAM with technologies like plasma arrays, which broaden absorption frequencies and improve radar cross-section reduction. These developments pave the way for enhanced applications in radar stealth, microwave transmission, and high-power microwave shielding, contributing to the reliability and efficiency of technological systems across multiple sectors [52, 8].

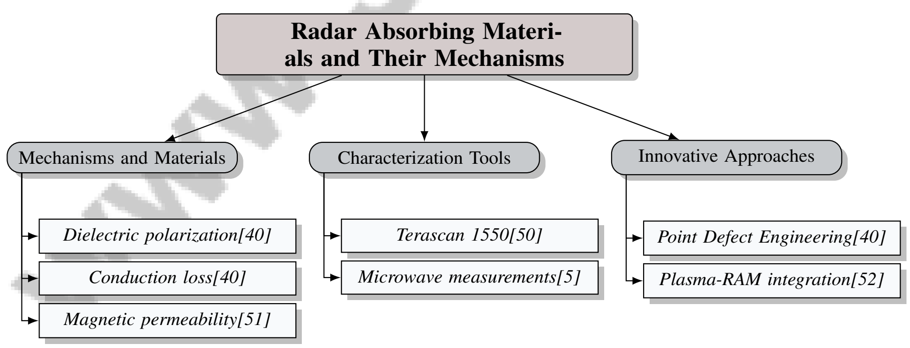

Figure 8: This figure illustrates the key mechanisms, characterization tools, and innovative approaches in the study of radar absorbing materials (RAM). It highlights dielectric polarization and conduction loss as primary mechanisms, the use of Terascan 1550 for characterization, and innovative methods like Point Defect Engineering and plasma-RAM integration for enhanced electromagnetic wave absorption.

7 Comparative Analysis of Shielding Materials

A comprehensive understanding of electromagnetic interference (EMI) shielding involves examining the properties and applications of various materials, focusing on their reflection and absorption mechanisms, the role of composite structures, and the practical implications of electromagnetic shielding effectiveness (EMI SE). This analysis highlights how different materials enhance the

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performance and reliability of electronic devices, particularly in the context of emerging technologies such as 5G communication [16, 53, 8, 7, 1]. The discussion begins with dielectric materials and radar absorbing materials (RAM), both crucial in EMI shielding technologies, emphasizing their unique properties, mechanisms, and practical applications to better understand their strengths and limitations in mitigating electromagnetic interference.

7.1 Comparative Analysis of Dielectric and Radar Absorbing Materials

Dielectric materials and radar absorbing materials (RAM) are pivotal in EMI shielding, each offering distinct advantages and mechanisms. Dielectric materials rely on dielectric loss processes, where polarization under an electromagnetic field leads to energy dissipation as heat [45]. This process is governed by the material's complex permittivity, which dictates its energy storage and dissipation capabilities [46]. Conversely, RAMs attenuate electromagnetic waves through dielectric polarization and conduction loss, optimized by methods like Point Defect Engineering to enhance permittivity [40].

The effectiveness of these materials in EMI shielding is assessed by their ability to attenuate electromagnetic waves across various frequencies. Dielectric materials are well-suited for applications requiring high dielectric constants and large band gaps, facilitating efficient energy storage and dissipation [48]. RAMs focus on reducing radar cross-sections by minimizing reflectance and enhancing absorption efficiency, as demonstrated by the Terascan 1550 system's capability to measure reflectance over a broad frequency range [50]. The composition of RAMs, particularly the balance between ferrite content and absorption characteristics, significantly impacts their performance [51].

In practical applications, dielectric materials are preferred in environments requiring stealth capabilities and high-frequency performance, enabling impedance matching and minimizing reflection [49]. RAMs are extensively used in military and aerospace sectors, where reducing radar visibility is paramount. Theoretical insights into RAMs, such as those derived from Noek's law, provide robust estimates for microwave measurements, ensuring precise control over electromagnetic interactions [5].

The comparative analysis reveals that dielectric and radar absorbing materials play distinct yet complementary roles in EMI shielding; dielectric materials primarily enhance absorption through conduction loss and polarization, while RAMs excel in reflection and scattering. This synergy ensures effective protection and optimal performance of electronic devices against electromagnetic pollution [40, 16, 8]. While dielectric materials are adept at energy storage and dissipation, RAMs provide superior absorption and stealth capabilities, making them vital across various technological domains requiring effective electromagnetic wave attenuation.

7.2 Trade-offs in Optical Transmittance and EMI Shielding

Balancing optical transmittance and electromagnetic interference (EMI) shielding effectiveness presents significant challenges in developing advanced materials for modern electronic applications. Achieving high optical transparency alongside effective EMI shielding is crucial for transparent conductive films in touch screens, displays, and solar cells. Traditional metal-based materials, though efficient in EMI shielding, often compromise optical transparency due to their inherent opacity [44].

Recent advancements have focused on transparent conductive films utilizing metal meshes, which balance transparency with shielding effectiveness. Metal mesh-based materials maintain high optical clarity while delivering robust EMI shielding, overcoming the limitations of traditional opaque materials [44]. This approach is particularly beneficial for infrared-transparent systems, where both optical transparency and EMI shielding are essential.

Incorporating carbon-based materials like graphene into transparent films has shown promise in achieving this balance. Graphene's exceptional properties, including high electrical conductivity and optical transparency, make it an ideal candidate for materials requiring both EMI shielding and optical transmittance [37]. Techniques such as layer-by-layer coating allow precise control over transparency and conductivity, enabling the design of materials tailored to specific application needs.

Furthermore, the use of hybrid composites and advanced fabrication techniques, including quasi-one-dimensional van der Waals materials, enhances the capacity to customize the optical and electromagnetic properties of materials [29]. These innovations highlight the potential for developing

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multifunctional materials that address the trade-offs between optical transmittance and EMI shielding, paving the way for their integration into a wide array of technological applications.

8 Recent Advances and Future Directions

8.1 Recent Advancements and Emerging Trends

Innovations in electromagnetic interference (EMI) shielding materials are focusing on multifunctional solutions to meet the demands of modern technology. Advanced fabrication methods, such as eco-friendly Fused Deposition Modeling (FDM) 3D printing, are enabling the creation of conductive metasurfaces with enhanced electromagnetic properties, promoting sustainable design [3]. Sandwich structures like the ANF/MXene/SSG configuration have achieved an EMI shielding effectiveness of 62.6 dB and a maximum impact force attenuation of 71.0%, making them ideal for wearable devices requiring both mechanical and electromagnetic performance [2].

In wireless communication systems, reconfigurable intelligent surfaces (RIS) are being integrated to enhance signal quality while mitigating EMI. A novel EMI cancellation scheme has been proposed, demonstrating superior performance compared to traditional methods, especially when EMI power approaches that of the main signal. This advancement underscores the importance of strategic interference management to improve average signal-to-interference-plus-noise ratio (SINR) and reduce outage probability [4]. Understanding electromagnetic shielding effectiveness (EMI SE) concepts is crucial for developing materials that effectively shield against EMI, ensuring reliability across diverse applications [16].

The trend toward multifunctional and flexible EMI shielding solutions is particularly pronounced in emerging technologies such as 5G communication. These materials not only mitigate harmful electromagnetic radiation but also emphasize sustainability and high performance, addressing the needs of modern electronic and communication devices. The integration of lightweight, multifunctional composites is essential, providing enhanced protection while remaining compatible with next-generation flexible electronics. This shift highlights the importance of innovative design strategies and the establishment of a "green EMI shielding" performance index, which together address the challenges of electromagnetic pollution and enhance the reliability and efficiency of technological systems across various sectors [8, 1].

8.2 Future Research Directions

The future of EMI shielding materials is poised for significant evolution through several promising research avenues. Optimizing sandwich layer compositions and structures could substantially enhance conductivity and overall material performance in practical applications [2]. This involves exploring novel combinations of materials and structural designs to maximize shielding effectiveness while preserving desirable mechanical properties.

Extending EMI cancellation schemes to multiple-input multiple-output (MIMO) systems represents another critical direction, broadening the applicability and efficacy of EMI shielding solutions in complex wireless communication environments, thereby improving signal quality and reducing interference [4]. Refining theoretical models to better account for the complexities of various materials and their interactions with electromagnetic waves is essential for enhancing predictive accuracy regarding shielding performance and facilitating the development of more effective materials [16]. Investigating novel nanofiller combinations and optimizing blending processes could yield more efficient biocomposites for EMI applications.

Research into alternative particle shapes and orientations, as well as the effects of different material combinations, could further enhance the anisotropic properties of dielectric materials, improving the design and functionality of materials used in EMI shielding applications. Enhancing the absorptivity of metasurfaces at oblique angles and investigating alternative materials, such as reconfigurable honeycomb structures with VO2 films, could significantly boost performance. Recent advancements have demonstrated a metamaterial absorber achieving over 90

Developing low-complexity channel estimation schemes tailored for EMI-aware environments is another important research avenue, optimizing communication system performance in the presence of EMI to ensure reliable data transmission. Improving printing conditions and exploring new filament

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materials could enhance the electromagnetic performance of printed metasurfaces, expanding their application in specialized areas [3].

These research directions highlight the potential for advancements in EMI shielding materials, aiming to improve performance metrics, enhance sustainability through eco-friendly materials, and broaden applicability across various technological sectors, particularly in the context of emerging flexible electronic devices, 5G communication technologies, and the need for reliable protection against electromagnetic pollution. The ongoing exploration of multifunctional composites and innovative design strategies underscores the critical role of EMI shielding in ensuring the integrity and efficiency of electronic systems [16, 8, 9, 53, 1].

9 Conclusion

Electromagnetic interference (EMI) shielding remains a pivotal concern in safeguarding the functionality and reliability of electronic systems across diverse technological sectors. This survey underscores the necessity for innovative EMI shielding materials that harmonize performance, cost-efficiency, and environmental sustainability. The exploration of various materials, including polymer foams, carbon-based foams, metal-based foams, dielectric materials, and radar absorbing materials, reveals significant potential for advancements in this field. Porous carbon-based materials and graphene-based epoxy composites emerge as promising candidates for effective microwave absorption and EMI shielding, respectively, due to their structural and compositional versatility.

The environmental impact of traditional electronics manufacturing and the growing challenge of electronic waste necessitate the development of more sustainable EMI shielding solutions. The integration of intelligent reconfigurable surfaces (IRS) offers advanced strategies for managing interference, demonstrating enhanced performance over conventional systems in EMI-prone environments. High-power intentional electromagnetic interference (IEMI) presents a formidable threat to electronic systems, while low-power IEMI requires precise targeting knowledge to be effective.

Future research should focus on optimizing material properties and exploring novel configurations, such as non-smooth geometries and three-dimensional structures, to improve EMI shielding efficacy. Achieving optimal material characteristics, such as the equivalent dielectric constant frequency (EDCF), is crucial for minimizing reflection losses and enhancing shielding performance. Addressing existing gaps in material optimization and exploring new methodologies for EMI shielding remain essential for advancing this field.

The study also highlights the degradation of uplink performance in RIS-aided CF massive MIMO systems due to EMI, particularly affecting user equipment with poor channel conditions. Iron-based materials with higher magnetic permeability are identified as superior in absorption performance, emphasizing the importance of optimizing dielectric and magnetic properties. The d'Alembert Wave Pulse Method and free-space characterization techniques prove valuable for visualizing electromagnetic wave behavior and accurately extracting material properties, respectively.

Continued research should aim to broaden bandwidth capabilities, refine production techniques for advanced materials like Few-Layered Mesoporous Graphene (FLMG), and enhance commercial viability. The potential for flexible electronics applications further underscores the importance of optimizing material compositions, such as the balance between Ag and Ni content. The proposed two-phase channel estimation scheme and renormalization methods offer promising directions for future theoretical and practical advancements in EMI shielding and related fields.

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