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# Research progress on surface wave attenuation of radar absorbing materials

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**Abstract:** Radar absorbing materials (RAMs), as a significant research direction in the field of electromagnetic wave protection, exhibit broad application prospects. In recent years, with the continuous development of radar detection technology and material absorbing technology, coupled with increasing application demands, the performance requirements for absorbing materials have gradually extended from traditional reflectivity suppression towards the simultaneous enhancement of both reflectivity suppression and surface wave attenuation. Surface waves, as a form of electromagnetic wave propagation along material surfaces, possess attenuation performance that directly influences the overall effectiveness of the absorbing material. This paper reviews the recent research progress concerning the surface wave attenuation performance of radar absorbing materials, first introducing the fundamental concepts and propagation characteristics of radar surface waves; subsequently, the research progress on the impact of three types of absorbing materials (magnetic loss RAMs, dielectric loss RAMs, and metamaterials) on surface wave attenuation performance is presented. Finally, based on current research trends, potential directions for enhancing the surface wave attenuation performance of future absorbing materials are proposed, and the pressing issues and challenges requiring urgent resolution within this field are identified.

**Keywords:** radar absorbing materials, surface wave, magnetic loss, dielectric loss, metamaterials

## 1. Introduction

With the rapid development and expanding application domains of radar technology, the demand for Radar Absorbing Materials (RAMs) has progressively increased, particularly in fields such as stealth technology, electronic countermeasures, and intelligent transportation. The fundamental function of RAMs is to reduce the reflection of radar waves and enhance the absorption of electromagnetic waves. However, traditional absorbing materials have primarily focused on the suppression of electromagnetic wave reflectivity, while their performance in attenuating surface waves has often been neglected. When electromagnetic waves are incident upon a conductor, surface currents (or creeping waves/surface waves) are excited and induced on the conductor's surface. These surface currents propagate along the conductor surface; when encountering electromagnetic discontinuities on the surface, they become sources of electromagnetic radiation. The existence of such surface waves was first predicted by Ritchie at Oak Ridge National Laboratory in the USA in 1957 [1]. Subsequent in-depth research revealed numerous novel properties of surface waves, attracting increasing attention from researchers, among whom Raether [2], Otto [3, 4], and Kretschmann are particularly notable [5].

Due to the long-range detection characteristics of radar, targets possess not only vertical reflecting surfaces but also large areas subject to grazing incidence electromagnetic waves. Significant grazing incidence results in strong surface currents forming on the target surface. Because of the inherent structural features of targets, numerous electromagnetic discontinuities inevitably form, which act as numerous radiation sources. The presence of these numerous radiation sources can significantly degrade the stealth effectiveness of a target. Consequently, the existence of surface wave scattering can substantially diminish the practical performance of RAMs. Therefore, enhancing the surface wave attenuation performance of absorbing materials has become a crucial direction in current research.

Surface wave attenuation performance is not only closely related to the electromagnetic properties of the material but also intrinsically linked to its surface morphology, structural design, and response characteristics across multiple frequency bands. Therefore, investigating the surface wave attenuation characteristics of different types of absorbing materials can provide theoretical support and practical basis for the design of highly efficient radar stealth materials. This paper reviews the relevant literature to explore the research progress on the surface wave attenuation performance of radar absorbing materials and outlines potential future research directions.

## 2. Introduction to radar surface waves

### 2.1. Basic types of surface waves

Surface waves studied to date can be broadly categorized into three types [6]: Surface Plasmon Polariton (SPP) waves, Dyakonov waves, and Tamm waves. Surface Plasmon Polariton (SPP) waves are surface electromagnetic waves excited at the interface between a metal plate and a dielectric material, which may be either isotropic or anisotropic. SPP waves represent the most extensively researched type of surface wave. A schematic model of SPP waves is provided in Figure 1.


**Figure 1.** Surface Plasmon Polariton wave model

### 2.2. Propagation characteristics of surface waves

The propagation characteristics of surface waves are typically determined by their dispersion relations. In certain material systems, surface waves can propagate with relatively low losses and exhibit strong stability within specific frequency ranges. The propagation path of surface waves is influenced by multiple factors, such as the electromagnetic parameters of the absorbing material on the metal surface and the external environmental electromagnetic field [7]. Generally, the attenuation constant β can be equivalently expressed as the sum of dielectric loss $\alpha_e$ and magnetic loss $\alpha_m$. Here, $\alpha_e$ and $\alpha_m$ satisfy the following equations:

$$\alpha_e = \frac{P_e}{2P_z} \qquad \alpha_m = \frac{P_m}{2P_z} \tag{1}$$

$$P_e = \frac{1}{2k_0} Z_0 \frac{\varepsilon'}{|\varepsilon|^2} \frac{1}{|\cos(k_2 a)|^2} \left[|\beta|^2\right] \int_0^a |\cos(k_2 y)|^2 dy + \left[|k_2|^2\right] \int_0^a |\sin(k_2 y)|^2 dy \tag{2}$$

$$P_m = \frac{1}{2} Z_0 k_0 \mu' \frac{1}{|\cos(k_2 a)|^2} \int_0^a |\cos(k_2 y)|^2 dy \tag{3}$$

$$P_z = \frac{1}{2k_0} Z_0 \frac{1}{|\cos(k_2 a)|^2} \left[ \frac{\beta'}{2k_1'} \left| \cos(k_2 a)^2 dy + Re\left(\frac{\beta}{\varepsilon}\right) \int_0^a |\cos(k_2 y)|^2 dy \right| \right] \tag{4}$$

where $P_e$ and $P_m$ represent the total dielectric loss energy and total magnetic loss energy per unit length along the z-axis, respectively, and $P_z$ denotes the total energy of surface wave propagation. The attenuation constant $\beta$ can be calculated using the above equations.

## 3. Research progress on surface wave attenuation of various absorbing materials

### 3.1. Magnetic loss absorbing materials

Magnetic absorbing materials, such as ferrites and magnetic composites, are widely utilized in Radar Absorbing Material (RAM) research. In recent years, surface wave testing techniques have matured significantly [8, 9]. Extensive experiments have demonstrated that magnetic RAMs exhibit strong surface wave attenuation performance, primarily attributed to their magnetic anisotropy and magnetic loss. These materials influence radar wave propagation through variations in permeability, effectively suppressing surface wave propagation.

Huang discovered that for high-frequency surface waves [10], RAM coatings can achieve strong attenuation absorption with minimal thickness, whereas low-frequency surface waves require thicker coatings. Combining Frequency-Selective Surfaces (FSS) with RAM coatings enables strong low-frequency surface wave attenuation even with thin coatings.

This finding suggests that alternating designs of pure RAM coatings and FSS-RAM composite coatings may achieve high surface wave attenuation across broad radar bands with minimal weight, facilitating balanced high-performance radar stealth for entire targets.

Wang et al. developed NiCuZn ferrite-based composites for the P-band [11], investigating their impact on P-band surface wave suppression. Using Stratton's surface wave attenuation calculation method, they analyzed the relationship between attenuation rate and coating thickness, identifying the attenuation bands for composites with varying ferrite absorber content. Results showed that increasing ferrite mass fraction enhanced electromagnetic parameters; at a 5:1 ferrite-to-paraffin ratio, a 10-mm composite exhibited optimal surface wave attenuation (>20 dB/m within 570–998 MHz).

Rao fabricated magnetic loss flexible RAMs via tape casting, demonstrating excellent absorption and electromagnetic properties [12]. Analysis of dispersion equations, electromagnetic field distributions, and attenuation tests confirmed effective surface wave suppression across 1–18 GHz, with attenuation intensifying at higher frequencies (see Figure 2). While limited in low frequencies, significant attenuation was achieved at 18 GHz (34.15 dB/m).

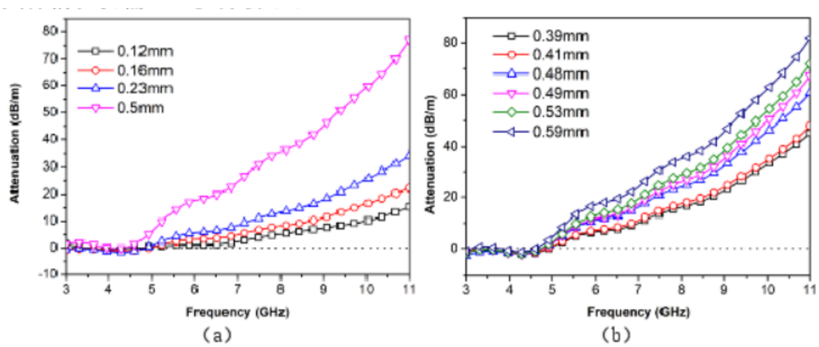


**Figure 2.** Surface wave attenuation test results: (a) single-layer sample; (b) multilayer sample

Zheng conducted theoretical calculations, simulations, and experiments on $FeCo@SiO_2$ coatings with both electric and magnetic loss [13]. Surface wave scattering peak angles were predicted via propagation models, coating thickness effects on attenuation coefficients were discussed, and contributions of electric/magnetic losses to attenuation were quantified. Results revealed that attenuation coefficients first increased then decreased with thicker coatings, dominated by magnetic loss.

Zhang et al. applied a 1-mm artificial magnetic RAM ( $\varepsilon_r$ =60, $tan\delta$ =0.6; $\mu_r$ =15, $tan\delta\mu$ =0.9) to the trailing edge of a 5-m trapezoidal wing (radius: 5 mm) [14]. Simulations proved that the coating reduced forward-sector scattering by suppressing trailing-edge surface waves, with efficacy dependent on design and coverage area.

## 3.2. Electric loss absorbing materials

Magnetic RAMs suffer from high weight, poor corrosion resistance, and mechanical fragility. Electric loss RAMs overcome these limitations but face challenges in achieving broadband performance under thickness constraints.

Li defined TM-mode surface wave attenuation impedance matching for single/multilayer RAMs, linking it to reflectivity impedance matching [15]. Analysis yielded electromagnetic parameter requirements for simultaneous reflectivity suppression and TM-mode surface wave attenuation. For multilayer electric loss RAMs, structural design should follow a gradient: electromagnetic parameters increase from top to bottom layers.

Liu et al. simulated graphene foam RAMs, varying thickness (10–30 mm), $\varepsilon'$ (80–120%), and $\varepsilon''$ (80–120%) [16]. Increasing thickness shifted attenuation peaks toward lower frequencies, reducing peak values and narrowing bandwidths. Higher $\varepsilon'$ broadened bandwidths and increased peak attenuation, while higher $\varepsilon''$ reduced bandwidths and peak values without shifting peaks. Optimal low surface wave attenuation requires thicker designs, lower $\varepsilon'$, and higher $\varepsilon''$.

Chopped carbon fibers—a resistive loss absorber—leverage resonance, eddy currents, and phase cancellation. Their anisotropic morphology yields unique electromagnetic interactions. Similar absorbers include activated, porous, and nanoscale carbon fibers, carbon nanotubes, SiC fibers, and modified fibers [17–20]. Research focuses on enhancing attenuation intensity, bandwidth, and thinness while ensuring lightweight, broadband, and corrosion-resistant performance. For instance: Xing et al [21].: 8.5-mm graded-impedance composite achieved <-10 dB reflectivity (3–18 GHz). Zhao et al [22].: 4-mm laminate (three 0.2–0.4 mm graded layers) achieved <-10 dB reflectivity (5–18 GHz). Liu et al [23].: 5.2-mm Jaumann absorber with multi-walled carbon nanotubes achieved 11.6 GHz -10 dB bandwidth.

Most studies optimize reflectivity via material selection and layer thickness but neglect surface wave attenuation. In practice, oblique microwave incidence excites surface waves on conductors, where attenuation capability critically impacts Radar Cross-

Section (RCS). Investigating surface wave attenuation mechanisms is thus vital for designing advanced RAMs.

### 3.3. Metamaterials

Recent advances in metamaterials have spurred research into surface wave attenuation. Current strategies exploit finely tuned array structures to manipulate surface waves. To simplify designs, attention has shifted to nonlinear surface waves, where external physical fields (e.g., intensity) modulate wave properties [24]. Figure 3 illustrates two typical nonlinear surface wave models.

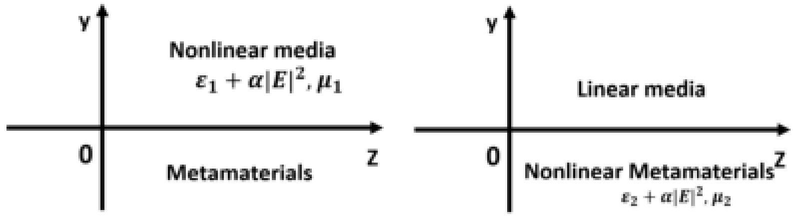


**Figure 3.** Two metamaterial-based nonlinear surface wave models

Zhu et al. designed a serpentine-patterned structure, improving surface wave attenuation [25]. Optimized electromagnetic parameters and patterning raised the upper cutoff frequency from 4 GHz to 8 GHz (see Figure 4), enabling broadband high-attenuation RAM designs.

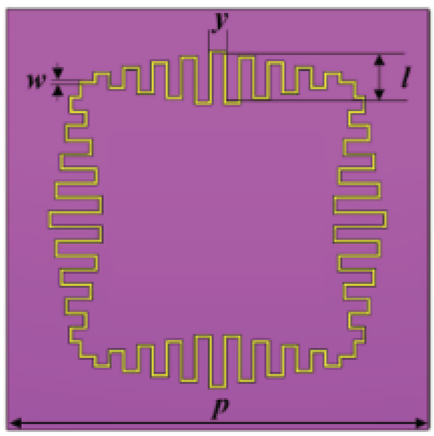


**Figure 4.** (a) Serpentine structure; (b) Attenuation constants with/without serpentine patterning

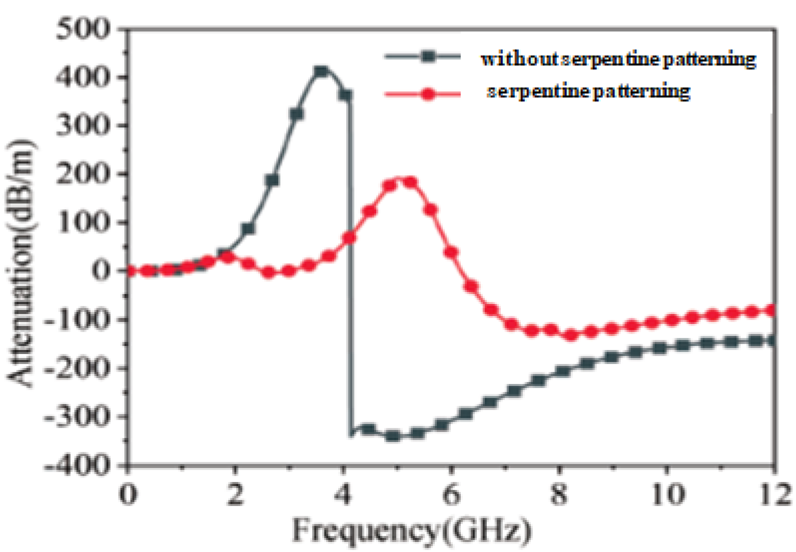


**Figure 4.** (a) Serpentine structure; (b) Attenuation constants with/without serpentine patterning

Zheng designed a magnetic metamaterial RAM using resistive ink-printed FSS, magnetic top layers, and dielectric substrates [13]. Simulations confirmed reduced RCS across incident angles via suppressed surface waves and specular reflection, achieving >90% absorption in S/C bands (2–8 GHz, 120% bandwidth) at 5-mm thickness—outperforming existing literature.

Zhang designed periodic-structure-enhanced RAMs, analyzing reflectivity and surface wave attenuation [26]. Improved low-frequency attenuation (1 GHz: 3.64 dB/m → 12.84 dB/m, see Table 1) was achieved by increasing thickness, optimizing electromagnetic parameters, multilayer stacking, and patterning resistive/metal films.

**Table 1.** Surface wave attenuation comparison at 1 GHz for different structures

| Structure | RAM | resistive films | Square resistive films | Square metal films |
|---|---|---|---|---|
| Attenuation(dB/m) | 3.64 | 5.01 | 11.3 | 12.84 |

## 4. Conclusions and perspectives

Research on surface wave attenuation in RAMs has gained momentum. Magnetic, electric loss, and metamaterial-based RAMs exhibit varying degrees of surface wave attenuation. However, limitations persist, such as poor low-frequency attenuation and narrow bandwidths. Future work should prioritize: (1) Multifunctional composites: Optimize conductive-magnetic hybrids for enhanced multi-type wave absorption. (2) Nanomaterials and microstructural design: Leverage nanotech and microengineering to boost broadband (especially low-frequency) attenuation. (3) Metamaterials and tunability: Develop smart RAMs with dynamically adjustable attenuation via metamaterials and external stimuli. Despite progress, theoretical and practical challenges remain. Advancements in materials science, metamaterial design, and intelligent control will drive next-generation high-performance RAMs.

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