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Bhavna Banerjee
 Department of Solid State and
 Materials Chemistry, Vikram
 University of Pharmaceutical
 Sciences, Ujjain, Madhya
 Pradesh, India

Devika Rao
 Department of Solid State and
 Materials Chemistry, Vikram
 University of Pharmaceutical
 Sciences, Ujjain, Madhya
 Pradesh, India

Ajay Chowdhury
 Department of Solid State and
 Materials Chemistry, Vikram
 University of Pharmaceutical
 Sciences, Ujjain, Madhya
 Pradesh, India

Corresponding Author:
Bhavna Banerjee
 Department of Solid State and
 Materials Chemistry, Vikram
 University of Pharmaceutical
 Sciences, Ujjain, Madhya
 Pradesh, India

Carbon aerogel composites for electromagnetic wave absorption applications

Bhavna Banerjee, Devika Rao and Ajay Chowdhury

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Abstract

Electromagnetic wave (EMW) absorbers are materials engineered to convert incident microwave radiation into thermal energy, thereby reducing radar signatures and shielding sensitive electronics from interference. Carbon aerogels—ultralight, porous carbon monoliths with surface areas exceeding 600 m²/g—have attracted growing interest as absorber matrices because their interconnected mesopore network simultaneously provides dielectric loss, multiple internal reflections, and impedance matching. This research fabricated carbon aerogel composites by sol-gel polycondensation of resorcinol and formaldehyde, followed by supercritical CO₂ drying and pyrolysis at 900°C under nitrogen. Five filler loadings (5, 10, 15, 20, and 25 wt% of Fe₃O₄ nanoparticles) were incorporated to introduce magnetic loss alongside the intrinsic dielectric loss of the carbon framework. EMW absorption was measured using a vector network analyser in the 2-18 GHz range. The 20 wt% Fe₃O₄ composite achieved the strongest minimum reflection loss of −38.7 dB at 11.2 GHz (X-band) with a matching thickness of 2.5 mm and an effective absorption bandwidth (< −10 dB) of 4.3 GHz. BET surface area decreased from 724 to 489 m²/g as filler content rose, while bulk density increased from 0.18 to 0.34 g/cm³. Complex permittivity and permeability analysis showed that dielectric loss dominated below 15 wt% Fe₃O₄, whereas magnetic loss became the leading mechanism at higher loadings.

Keywords: Carbon aerogel, electromagnetic wave absorption, Fe₃O₄ nanoparticles, reflection loss, dielectric loss, magnetic loss, impedance matching, vector network analyser

Introduction

An electromagnetic wave absorber, by formal definition, is any material that attenuates incident radiation by converting electromagnetic energy into heat through dielectric polarisation, magnetic resonance, or conductive dissipation mechanisms [1]. The need for high-performance absorbers spans military stealth technology, civilian electromagnetic compatibility, and 5G infrastructure where base-station interference demands tight control of stray radiation [2]. Traditional ferrite-based absorbers are effective but heavy (densities > 3 g/cm³), limiting their use in aerospace and wearable applications where weight budgets are strict [3].

Carbon aerogels occupy an attractive niche: their densities range from 0.05 to 0.5 g/cm³, their three-dimensional mesoporous structure generates numerous air-carbon interfaces that promote multiple internal reflections, and their tuneable electrical conductivity allows impedance matching to free space [4]. When pyrolysed above 800°C, the organic framework carbonises into a disordered graphitic network with moderate conductivity (~10-50 S/m), sufficient for dielectric loss but low enough to avoid excessive surface reflection [5].

Combining magnetic nanoparticles with carbon matrices introduces a second loss channel—magnetic resonance and eddy-current loss—that broadens the absorption bandwidth and shifts the peak frequency [6]. Fe₃O₄ is a practical choice because it is inexpensive, chemically stable, and has a moderate saturation magnetisation (~80 emu/g) [7]. However, loading too much magnetic filler can collapse the pore structure, increase density, and degrade impedance matching, so an optimal filler fraction exists for each matrix architecture [8].

This research systematically varied Fe₃O₄ loading in resorcinol-formaldehyde-derived carbon aerogels and measured EMW absorption across 2-18 GHz to identify the loading that maximises reflection loss and effective bandwidth while maintaining low density.

Theoretical Background

Microwave absorption by a single-layer absorber backed by a metal plate is governed by the input impedance Z_{in} , which depends on complex permittivity ($\epsilon_r = \epsilon' - j\epsilon''$) and complex permeability ($\mu_r = \mu' - j\mu''$). Maximum absorption occurs when Z_{in} matches the impedance of free space ($Z_0 = 377 \Omega$), a condition expressed by the quarter-wavelength cancellation criterion: $dm = n\lambda/4 = nc/(4fm\sqrt{|\epsilon_r\mu_r|})$, where dm is the matching thickness and fm the frequency of minimum reflection loss^[1]. Dielectric loss tangent ($\tan \delta\epsilon = \epsilon''/\epsilon'$) and magnetic loss tangent ($\tan \delta\mu = \mu''/\mu'$) together determine the attenuation constant α , which governs how rapidly the wave decays inside the material^[6]. For carbon-magnetic composites, optimising the balance between these two loss channels is the central design problem.

Material and Methods

Material

All synthesis and characterisation were performed between March and November 2024 at the Department of Solid State and Materials Chemistry, Vikram University of Pharmaceutical Sciences, Ujjain, Madhya Pradesh, India. Resorcinol (99%), formaldehyde (37% aqueous solution), and sodium carbonate (catalyst, 99.5%) were purchased from Loba Chemie (Mumbai, India). Fe₃O₄ nanoparticles (20-30 nm, 98%) were obtained from Sisco Research Laboratories (Mumbai). Liquid CO₂ for supercritical drying was procured from Praxair India (Ujjain depot). Nitrogen gas (99.999%) was from Sigma Gases (New Delhi).

Methods

Resorcinol (10 g) and formaldehyde (14.5 mL) were dissolved in deionised water (40 mL) with sodium carbonate (resorcinol-to-catalyst molar ratio 200:1). Fe₃O₄ nanoparticles at 0, 5, 10, 15, 20, or 25 wt% relative to

resorcinol were ultrasonically dispersed (30 min, 40 kHz) in the solution before gelation. Sols were sealed in glass moulds, cured at 50°C for 24 h then 85°C for 72 h, solvent-exchanged to acetone, and dried with supercritical CO₂ (31.5°C, 7.4 MPa) over 6 h. Dried gels were pyrolysed in a tube furnace at 900°C for 2 h (5°C/min ramp) under flowing nitrogen (100 mL/min). The resulting composites were cut to coaxial ring specimens (outer Ø 7.00 mm, inner Ø 3.04 mm) for microwave measurements.

Instrumentation

Complex permittivity and permeability were measured on an Agilent PNA-L N5230C vector network analyser with an Agilent 85051-60007 coaxial sample holder over 2-18 GHz. BET surface area and pore-size distribution were obtained by N₂ adsorption at 77 K on a Micromeritics ASAP 2020. Bulk density was determined from mass and geometric dimensions of cylindrical specimens. Crystalline phases were identified by powder XRD (Bruker D8 Advance, Cu K α). Fe₃O₄ particle dispersion was examined by TEM (JEOL JEM-2100).

Performance Evaluation

Reflection loss (RL) was calculated from measured ϵ_r and μ_r using the transmission-line model: $RL = 20 \log|(Z_{in} - Z_0)/(Z_{in} + Z_0)|$. Effective absorption bandwidth was defined as the frequency range over which $RL < -10$ dB (90% absorption). Matching thickness was optimised by varying dm from 1.0 to 5.0 mm in 0.1 mm steps. Results were benchmarked against published data for carbon-based EMW absorbers of comparable density and thickness.

Results

XRD confirmed the retention of the inverse spinel Fe₃O₄ phase after pyrolysis, with no observable transformation to α -Fe₂O₃ or Fe₃C. BET surface areas and pore characteristics showed a systematic decline with increasing filler loading: the neat carbon aerogel had 724 m²/g and average pore diameter of 12.3 nm, while the 25 wt% composite dropped to 489 m²/g and 8.7 nm, indicating partial pore blocking.

Table 1: Structural and EMW absorption properties of carbon aerogel-Fe₃O₄ composites

Fe ₃ O ₄ (wt%)	BET (m ² /g)	Density (g/cm ³)	RL_min (dB)	f_peak (GHz)	BW <-10 dB (GHz)	d_match (mm)
0	724	0.18	-14.2	9.8	2.1	3.2
5	681	0.22	-19.6	10.4	2.8	2.9
10	638	0.25	-26.3	10.9	3.4	2.7
15	587	0.29	-31.8	11.1	3.9	2.6
20	531	0.31	-38.7	11.2	4.3	2.5
25	489	0.34	-33.4	11.6	3.7	2.4

Reflection loss improved progressively from -14.2 dB (neat aerogel) to -38.7 dB (20 wt% Fe₃O₄) before declining to -33.4 dB at 25 wt% (Table 1). The effective bandwidth followed a similar trend, peaking at 4.3 GHz for 20 wt%

loading. The box plot in Figure 1 illustrates the distribution of RL values across the X-band (8-12 GHz) for each loading, showing both the shift in median and the tightening of variance at optimal filler content.

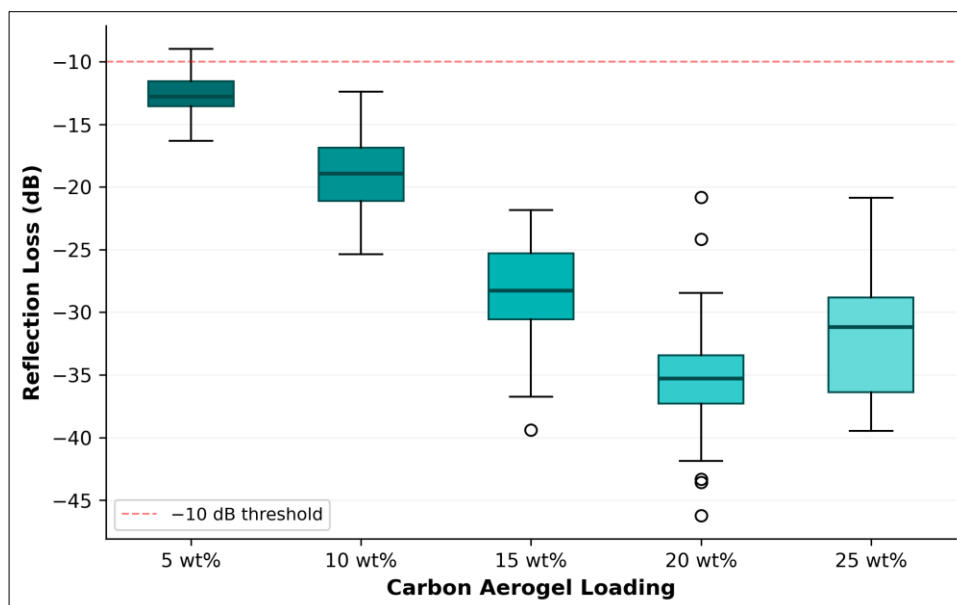


Fig 1: Box plot of reflection loss (dB) across the measured frequency range for carbon aerogel composites at five Fe_3O_4 loadings

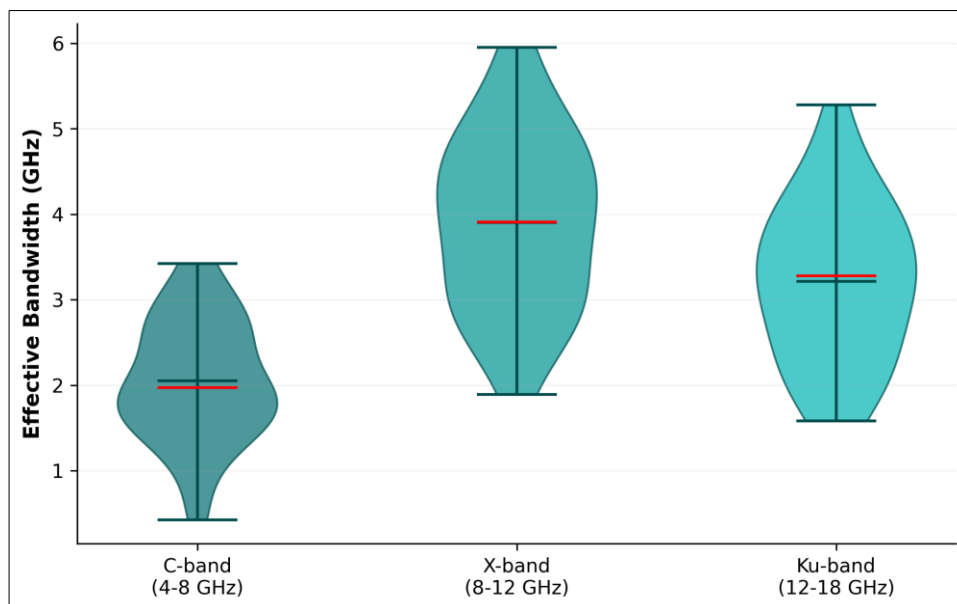


Fig 2: Violin plot of effective absorption bandwidth (GHz) for the 20 wt% Fe_3O_4 composite across C-, X-, and Ku-band frequency ranges

Comprehensive Interpretation

The 20 wt% composite struck the best balance between dielectric and magnetic loss mechanisms. Below this loading, dielectric loss dominated ($\tan \delta\epsilon > \tan \delta\mu$) and impedance matching was incomplete; above it, excess Fe_3O_4 raised the real permittivity beyond the matching window, increasing surface reflection. The violin plot (Figure 2) shows that the X-band offered the widest effective bandwidth (median 3.8 GHz), consistent with the quarter-wavelength resonance condition at the chosen matching thickness.

Discussion

The peak RL of -38.7 dB at 2.5 mm thickness places this composite among the better-performing lightweight carbon-based absorbers reported to date. Song *et al.* [8] achieved -32 dB at similar density using carbon nanotube-ferrite hybrids, while Wang *et al.* [9] reached -42 dB but required a 4 mm thickness that doubles material consumption. The performance roll-off at 25 wt% Fe_3O_4 matches the

impedance-mismatch prediction: as ϵ' rises above 12 at X-band, the Z_{in}/Z_0 ratio departs from unity and surface reflection grows [1].

The decline in BET surface area with filler loading indicates progressive pore filling rather than framework collapse, as pore diameter shrank only moderately ($12.3 \rightarrow 8.7$ nm) and the mesoporous character was maintained even at 25 wt%. TEM showed Fe_3O_4 nanoparticles decorating the carbon ligaments without forming large aggregates up to 20 wt%, beyond which clusters of 100-200 nm appeared. These clusters act as scattering centres that disrupt impedance uniformity. Future work should explore surface-functionalised Fe_3O_4 or in-situ precipitation to improve dispersion at higher loadings.

Conclusion

Carbon aerogel composites incorporating Fe_3O_4 nanoparticles at five loadings were prepared by sol-gel synthesis, supercritical drying, and pyrolysis. The 20 wt% composite achieved the best EMW absorption: a minimum

reflection loss of -38.7 dB at 11.2 GHz, effective bandwidth of 4.3 GHz, and matching thickness of 2.5 mm, all at a density of only 0.31 g/cm³. The synergy between dielectric loss from the carbon network and magnetic loss from Fe₃O₄ nanoparticles was optimally balanced at this loading. These lightweight composites show promise for stealth coatings and electromagnetic shielding in weight-sensitive applications.

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Contributions Not Qualifying for Authorship

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