



A comprehensive design framework for lightweight 3D-printed radar absorbers integrating material, process, and geometry optimization

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ABSTRACT

This study presents a comprehensive framework for the development and evaluation of radar-absorbing materials (RAMs) by combining optimized composite formulation with additive manufacturing strategies. Unlike many existing studies that remain largely theoretical or rely on flat, fully dense printed plates, the proposed approach introduces an application-oriented framework that integrates material selection, process optimization, and three-dimensional geometry. Initial specimens were prepared via conventional thermoplastic processing and compression molding, allowing detailed rheological, thermomechanical, and microstructural characterizations. These rheological insights were further employed as predictive indicators of FDM printability, enabling defect-free filament extrusion and geometric stability during fabrication. These insights were then used to guide and optimize 3D printing parameters, aiming to replicate or exceed the performance of molded references through lightweight, geometrically adaptable structures. Electromagnetic properties were first assessed using coaxial airline measurements in the X-band to optimize filler content and absorber thickness selection, and then validated through free-space antenna tests. Finally, antenna-based measurements were used to investigate the effects of geometric parameters such as pyramid height and infill ratio on absorption performance. Among 3D-printed structures, Concentric infill best matched the performance of compression-molded references. FS-20 pyramidal absorber (20 mm base) geometries enabled broadband absorption ($RL < -10$ dB, 9–12.5 GHz). Infill reduction from 100 to 30% provided a 58% weight saving while preserving deep RL dips (≈ -25 dB) and bandwidth. Overall, this study establishes a quantitatively validated material–process–geometry integration strategy that enables simultaneous broadband absorption and substantial weight reduction, offering a scalable and application-ready pathway beyond conventional flat or fully dense RAM designs.

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1 Introduction

Radar-absorbing materials (RAM) play a pivotal role in the development of stealth technologies by suppressing the backscattering of incident electromagnetic waves. These materials are designed to reduce the radar cross section (RCS) of military platforms, thereby enhancing concealment from active detection systems. Historically, RAMs were developed primarily for use in high-speed aerial vehicles such as fighter jets and missiles, where resistance to extreme mechanical stress and high-temperature conditions were a top priority [1–3]. However, with the rapid evolution of drone technology and the growing use of unmanned aerial vehicles (UAVs) in modern defense systems, the requirements for RAMs have begun to shift significantly [4, 5]. Today's lightweight, slow-flying UAVs demand not only effective electromagnetic wave attenuation but also strict compliance with geometric adaptability and mass reduction. These platforms often feature highly complex surface geometries, necessitating conformal absorber structures that can be precisely integrated without compromising aerodynamics or maneuverability. Moreover, operational doctrines involving swarms of drones require scalable production of application-specific components that are both low cost and rapidly manufacturable. This has brought forth the need for alternative manufacturing strategies capable of supporting design flexibility, weight optimization, and integration across a wide range of UAV configurations. Additive manufacturing (AM), particularly fused deposition modeling (FDM), has emerged as a compelling approach to meet these evolving needs. Among various additive manufacturing (AM) techniques, Fused Deposition Modeling (FDM) is advantageous due to the shear-dominated extrusion environment inherent to the process, which can influence filler dispersion and spatial distribution within the polymer matrix. Unlike resin-based or powder-bed methods, the controlled melt flow at the nozzle may assist in establishing interconnected conductive pathways at high filler loadings, as supported by the rheological percolation behavior observed in this study. Such microstructural organization contributes to enhanced interfacial polarization and dielectric loss properties [6]. Furthermore, FDM allows for the precise fabrication of complex geometries with high material efficiency and low operational costs, providing a scalable pathway for high-performance electromagnetic absorbers [7]. Unlike traditional

manufacturing methods, FDM offers the capability to fabricate absorbers with tailored external geometries as well as tunable internal architectures, such as controlled infill density. These capabilities enable engineers to achieve structural and electromagnetic performance targets simultaneously while reducing material usage and production time. Furthermore, the potential to formulate composite filaments with customized properties expands the design space even further, allowing multi-functional materials to be integrated directly into the manufacturing process. As a result, 3D printing offers a direct path toward the production of lightweight, application-driven RAMs for next-generation UAV platforms [8, 9].

A growing number of studies have focused on the development of radar-absorbing materials (RAMs) using additive manufacturing (AM) techniques, particularly fused deposition modeling (FDM), due to their potential for rapid prototyping, geometric flexibility, and cost-effective processing [10–13]. In these works, a wide range of thermoplastics such as polylactic acid (PLA) [14], acrylonitrile butadiene styrene (ABS) [15], and thermoplastic polyurethane (TPU) [16] have been reinforced with various functional fillers, including magnetic and dielectric additives, to achieve desirable electromagnetic (EM) absorption characteristics. These fillers include carbon-based particles (e.g., carbon black, graphene, CNTs), ferrites, or other lossy media intended to enhance attenuation in the desired frequency ranges, particularly within the X-band. While promising results have been obtained, most of these studies tend to focus on either the material composition or the external absorber geometry, with limited attention to their combined effects. In composition-oriented research, although improvements in *RL* have been reported, the rheological behavior, mechanical robustness, and printability of the resulting filaments have often been overlooked. As a result, the optimized EM performance often comes at the expense of processing quality or part reliability, restricting the practical scalability and compatibility of such filaments with standard FDM printers.

Conversely, geometry-focused studies have investigated the shape and dimension of absorbers, commonly pyramidal, wedge, or multilayer structures, mainly through numerical simulations or limited experimental validation [17–22]. These works, however, rarely explore the internal structural parameters unique to 3D printing, such as infill density and pattern, which can significantly affect both dielectric

properties and mechanical integrity. Since lightweight structures are crucial in aerial platforms such as drones and unmanned vehicles, neglecting these internal design features limits the overall optimization of weight-to-performance ratios. Furthermore, a significant gap exists in terms of benchmarking AM-fabricated RAMs against those produced via conventional processing techniques such as compression molding. Without such comparisons, the benefits and limitations of 3D-printed absorbers remain unclear, particularly with regard to their long-term EM stability, mechanical endurance, and scalability. Another area that remains largely unexplored is the systematic study of how critical parameters, such as pyramid height, infill ratio, and material rheology, interact and influence radar absorption performance. Although isolated studies have addressed these factors individually, a comprehensive evaluation that integrates these elements into a unified design–process–performance framework is still lacking. This limits the development of truly application-ready materials that balance electromagnetic attenuation, mechanical durability, and manufacturability.

In this study, a comprehensive approach was undertaken to develop and evaluate high-performance radar-absorbing materials (RAMs) using both conventional thermoplastic processing and additive manufacturing techniques. Initially, composite formulations were prepared via extrusion and subsequently shaped by compression molding to establish reference specimens. These reference samples were systematically characterized in terms of their rheological behavior, viscoelastic response (DMA), and micromechanical attributes to build a robust baseline for material performance. Building on this baseline, dielectric parameters were measured to identify the optimum composition and thickness for effective microwave attenuation. These optimized formulations were then fabricated using fused deposition modeling (FDM), where different printing strategies were explored to replicate, as closely as possible, the properties of compression-molded specimens. Subsequently, the dielectric response predicted from coaxial measurements was verified by free-space antenna tests, ensuring realistic assessment of microwave absorption performance. Finally, the unique capabilities of 3D printing were leveraged to investigate geometric optimization and lightweighting strategies. Variations in infill ratio and internal architecture were systematically introduced to reduce mass while maintaining

or enhancing attenuation efficiency. Through this stepwise approach, the study not only establishes a direct comparison between traditional and additive manufacturing methods but also demonstrates a scalable pathway for producing RAM components with tailored electromagnetic, mechanical, and structural properties suitable for practical deployment.

2 Materials and method

2.1 Materials

The matrix polymer employed in this study was a binary blend comprising 80 wt% polylactic acid (PLA, Ingeo 4043D, NatureWorks, density: 1.24 g/cm³) and 20 wt% thermoplastic polyurethane (TPU, Ravathane A60, Ravago Petrochemicals, density: 1.15 g/cm³). Throughout the study, this blend is denoted as PB for clarity and brevity. As the functional filler, nickel-coated carbon (NiC) was used, commercially known as E-fill 2805 (Oerlikon). The NiC particles exhibit a core-shell morphology, consisting of carbon cores uniformly coated with metallic nickel (≈ 75 wt% Ni, 25 wt% C). The average particle size is 44 μ m (325 mesh) with a bulk density of 5.0 g/cm³. For compositional clarity, the prepared composites are denoted as xNiC, where x corresponds to the NiC loading by weight (e.g., 60 NiC represents PB containing 60 wt% NiC).

2.2 Methods

2.2.1 Test sample preparation

Before processing, PLA and TPU granules were dried in a vacuum oven at 60 °C for 4 h to remove residual moisture, while NiC powders were vacuum-dried at 80 °C for 24 h to minimize oxidation. The dried components were premixed at filler loadings of 10–60 wt% and compounded in a co-rotating twin-screw extruder (Kökbir RTXT18, L/D = 25, 200 rpm). The temperature profile from feed to die was 30, 60, 180, 190, and 200 °C. The extrudates were air-cooled, pelletized, and then reprocessed in a single-screw filament extruder (Filamex FX-20, Turkey; screw diameter: 20 mm, L/D: 20) operated at a temperature profile of 170–190 °C, a screw speed of 15 rpm, a die diameter of 2 mm, and a haul-off speed of 17 rpm, using air cooling to produce filaments with a uniform diameter of 1.75 ± 0.05 mm.

For dielectric testing, reference plaques ($30 \times 30 \times 2 \text{ mm}^3$) were prepared by compression molding at 200°C under 7 MPa for 5 min, followed by cold pressing for 5 min. Identical dimensions were also fabricated by FDM, using a Zaxe Z3 system equipped with a 0.8-mm brass nozzle and an enclosed build chamber maintained at approximately 25°C . Slicing and toolpath generation were performed using the native Zaxe slicing software (Zaxe Desktop), which enabled precise control over extrusion parameters and infill geometry. Across all prints, consistent settings were applied to ensure reproducibility and comparability of results. The extrusion temperature was fixed at 200°C and the bed temperature at 60°C . A layer height of 0.40 mm and a line width of 0.80 mm (corresponding to 100% of the nozzle diameter) were used throughout. Two perimeters (shells = 2) and two top and bottom solid layers (2/2) were selected to promote structural sealing and dimensional fidelity. Retraction was disabled to prevent under-extrusion and flow interruptions, particularly under high-viscosity, filler-rich flow conditions, and the part-cooling fan operated at full speed (100%) from the first layer to facilitate thermal stabilization. A constant print speed of 30 mm/s and a maximum jerk limit of 5 mm/s were employed to minimize extrusion fluctuations and preserve path accuracy. All specimens were designed as $30 \times 30 \times 2 \text{ mm}^3$ plaques and printed at a nominal infill density of 100%. However, the effective material continuity was strongly dictated by the infill architecture. Three distinct slicing-defined infill strategies were selected: (i) Grid, consisting of $0^\circ/90^\circ$ raster orientation with periodic voids at line intersections; (ii) Cubic Subdivision, characterized by $\pm 45^\circ$ raster patterns forming a sparse volumetric network; and (iii) Concentric, composed of contour-following loops with minimal internal porosity.

All 3D-printed structures in this study, including dielectric test specimens, architectural variants, and antenna absorber designs, were fabricated using identical FDM parameters to ensure consistency across processing conditions. For all antenna measurements, the same concentric infill pattern was used. A 100% (concentric) flat plate ($100 \times 100 \times 1.6 \text{ mm}^3$) was first printed to serve as the substrate, and pyramidal absorber units were subsequently printed directly onto this plate. Each pyramid had a $20 \times 20 \text{ mm}^2$ base, while the heights were varied as 10, 20, and 30 mm to study the influence of vertical dimension on electromagnetic performance. The three corresponding designs were

coded as FS-10, FS-20, and FS-30, respectively, where the numerical label represents the pyramid height in millimeters. These pyramids were arranged in 5×5 periodic arrays across the plate, forming geometrically uniform and well-aligned structures suitable for free-space reflection measurements. In addition, cubic pyramids with dimensions of $20 \times 20 \times 20 \text{ mm}$ were printed in the same manner on the flat plate substrate in 5×5 periodic arrays, using internal infill ratios of 0, 30, and 50% to implement a lightweighting strategy aimed at reducing mass while maintaining comparable absorption performance.

2.2.2 Characterizations

Rheological measurements were carried out on all composites using a rotational dynamic oscillatory rheometer (Discovery Hybrid Rheometer-3, TA Instruments) equipped with 25 mm parallel plates and a $1000 \mu\text{m}$ gap. All granules obtained from filament extrusion were vacuum-dried prior to testing, and measurements were performed at 200°C . Steady-shear flow tests were conducted in the shear-rate range of $0.1\text{--}50 \text{ s}^{-1}$ using a logarithmic sweep. An equilibration time of 5 s and an averaging time of 20 s were applied at each point to ensure stable readings.

For thermomechanical testing, extruded granules were hot-pressed into sheets under the same conditions as dielectric specimens, yielding films with a thickness of approximately 0.3 mm. Rectangular strips with dimensions of $20 \times 10 \times 0.3 \text{ mm}^3$ were cut from these films and used as DMA specimens. Dynamic mechanical analysis (DMA) was performed on a Discovery Hybrid Rheometer (Discovery Hybrid Rheometer-3, TA Instruments). Temperature sweep tests were conducted in oscillatory mode with a fixed axial displacement of $20 \mu\text{m}$. The specimens were heated from 25 to 200°C at a linear rate of $4^\circ\text{C}/\text{min}$, while oscillation was applied at 1.0 Hz. Throughout the test, the storage modulus (E'), loss modulus (E''), and damping factor ($\tan \delta$) were continuously recorded as functions of temperature.

The dielectric and electromagnetic properties of the composites were evaluated using a vector network analyzer (VNA, Keysight FieldFox N9926A) equipped with a coaxial airline fixture (Keysight 85055AR03). Prior to measurement, a full two-port calibration of the airline system (open–short–load–thru) was performed to eliminate systematic errors arising from the cables,

connectors, and the sample holder. The complex relative permittivity (ϵ' , ϵ'') and permeability (μ' , μ'') were obtained from measurements conducted in the X-band frequency range (8.0–12.5 GHz) by applying standard transmission/reflection analysis.

To predict the radar-absorbing performance, reflection loss (RL) was modeled using transmission-line theory. The reflection loss (RL) was calculated using Eqs. (1–4) as follows:

$$RL = 20 \log \left| \frac{Z_i - Z_0}{Z_i + Z_0} \right| \quad (1)$$

$$Z_i = \eta_k \frac{Z_L \cos(\beta t) + j\eta_k \sin(\beta t)}{\eta_k \cos(\beta t) + jZ_L \sin(\beta t)} \quad (2)$$

$$\beta = 2\pi f \sqrt{\mu_0 \epsilon_0} \sqrt{\mu_r \epsilon_r} = 2\pi f \sqrt{\mu_0 \epsilon_0} \sqrt{(\mu' - j\mu'')(\epsilon' - j\epsilon'')} \quad (3)$$

$$\eta_k = \sqrt{\frac{\mu_k}{\epsilon_k}} \quad (4)$$

Here, Z_0 is the intrinsic impedance of free space, Z_i is the input impedance of the absorber, f is the frequency, t is the sample thickness, and ϵ' , ϵ'' , μ' , μ'' are the real and imaginary components of complex permittivity and permeability, respectively. β denotes the propagation constant and governs wave attenuation and phase behavior inside the absorber. η_k represents the intrinsic impedance of the material, and Z_L is the load impedance at the backing interface. These equations were employed to generate reflection loss contour maps as a function of frequency and thickness, enabling comparative analysis of absorber designs [23].

Free-space reflection measurements (S_{11}) were performed to evaluate the impedance matching and absorption behavior of the absorber structures under realistic electromagnetic conditions. The reflection results are presented as reflection loss (RL, in dB) for clarity. A pair of standard gain horn antennas (8.0–12.5 GHz) connected to the VNA (Keysight Field-Fox N9926A) were positioned in a transmit–receive configuration. The printed absorber specimens ($100 \times 100 \text{ mm}^2$) were mounted on a metallic backing plate and placed at a fixed distance of 15 cm from the transmitting antenna. This separation corresponds to more than three wavelengths in the X-band and is widely adopted in similar free-space setups. The present configuration can be regarded as a quasi-far-field

arrangement, in which any residual near-field contributions were minimized by calibration and consistent sample positioning.

3 Result and discussion

3.1 Melt flow behavior and processability

To specifically evaluate the processability of the developed composites in the context of extrusion-based 3D printing, rheological analysis in this study was deliberately limited to steady-shear flow tests. Unlike frequency sweep or oscillatory tests that probe microstructural viscoelasticity, flow measurements were chosen due to their direct relevance to practical melt behavior under shear, such as during filament extrusion and layer deposition. It should be noted that frequency-dependent rheological properties of similar NiC-filled PB systems have been extensively studied in our previous works [24]. Therefore, the current focus is on quantifying shear-rate-dependent viscosity to assess flow resistance during printing and melt stability post-deposition, which are critical for predicting print quality and dimensional fidelity. The steady-shear viscosity curves of NiC composites are presented in Fig. 1. As expected, all formulations display pronounced non-Newtonian shear-thinning behavior, which is characteristic of polymer-based systems subjected to increasing shear rates. In the range of 0.1 – 10 s^{-1} , samples containing up to 40 wt% NiC

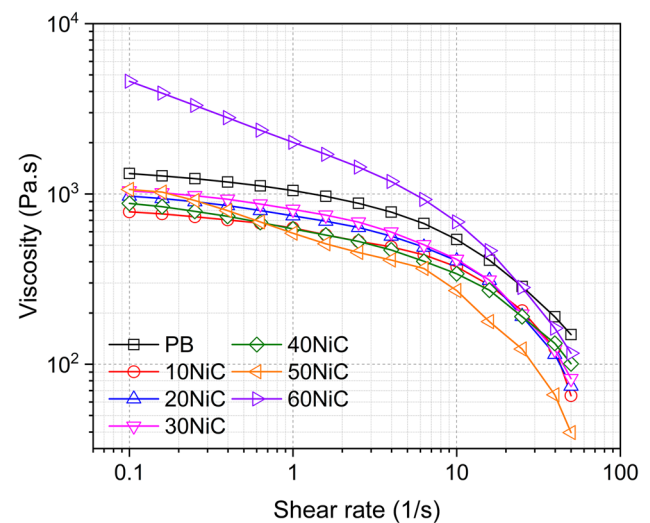


Fig. 1 Viscosity curve of the samples

exhibit a quasi-plateau region with gradually decreasing viscosity, followed by a sharp drop beyond $\sim 10 \text{ s}^{-1}$. This low-shear regime likely corresponds to limited chain orientation and/or insufficient shear energy to disrupt polymer entanglements or induce filler rearrangement. In the neat PB matrix, the slight downward slope within this regime may arise from the phase incompatibility between PLA and TPU, which facilitates the earlier onset of molecular alignment. Upon NiC addition, this slope becomes steeper, suggesting that the presence of fillers, particularly with weak polymer–filler affinity, may lead to early disruption of fragile filler clusters or insufficiently bound agglomerates under increasing shear. At 50 wt% NiC, the flow behavior changes qualitatively. Although the viscosity at very low shear rates increases, the system exhibits a dramatic viscosity drop under moderate-to-high shear rates. This nonlinearity is likely associated with pre-percolated, unstable filler networks or local agglomerates that rapidly disintegrate due to poor interparticle cohesion. In contrast, at 60 wt% NiC, a robust and stable filler network appears to be established: the viscosity at low shear rates increases significantly and remains elevated across a broader shear window. Unlike 50 wt%, the drop in viscosity here is more gradual, indicating that the dominant mechanism transitions from structural breakdown to orientation-driven shear thinning. Rather than disintegrating, the percolated network appears to reorganize and align under shear, maintaining continuity while adapting to flow. Another noteworthy feature observed in Fig. 1 is that the viscosity values do not increase monotonically with filler content. This nonlinear trend is evident at both low and high shear rates. Up to 50 wt% NiC, all composites exhibit lower viscosity than the neat matrix in the low-shear regime, indicating that the incorporation of filler initially promotes flow rather than impeding it. Such behavior implies that polymer–polymer interactions dominate over polymer–filler interactions in this composition range. The weak filler–matrix affinity, combined with interfacial slippage at filler surfaces, facilitates chain mobility and reduces resistance to flow. In this context, the decrease in viscosity can be attributed to interfacial decoupling mechanisms, where the introduction of fillers leads to partial disruption of polymer–polymer entanglements without establishing a robust filler network. However, at 60 wt% NiC, this trend reverses abruptly. The viscosity not only exceeds that of the matrix but does so significantly at low shear rates,

suggesting the emergence of a percolated, rigid filler network. This network imposes a mechanical locking effect, constraining the movement of polymer chains via interparticle contacts rather than compatibility. Unlike interfacial adhesion-driven reinforcement, this type of restriction arises from physical confinement, where polymer chains are entrapped within a quasi-static filler skeleton. As the shear rate increases, this network undergoes orientation and reorganization, gradually alleviating the confinement. This allows polymer chains to align and flow more freely, leading to a sharp viscosity drop at high shear rates—so much so that the viscosity of the 60 NiC composite falls below that of the neat polymer in this region. This behavior reflects a dual regime: a low-shear regime dominated by filler-induced jamming, and a high-shear regime where orientation overrides confinement, enabling enhanced flow. These findings further support the hypothesis that the 60 wt% NiC composition marks the transition from filler-dominated dissipation (interfacial slippage, fragile cluster breakup) to network-controlled restriction, where flow resistance stems from architectural entanglement rather than classical viscoelasticity.

To quantitatively analyze the observed non-Newtonian behavior, the experimental viscosity–shear-rate curves were fitted with the Cross model, which effectively describes the transition from the low-shear Newtonian-like regime to shear thinning at higher shear rates. The selection of this model was based not only on its compact form but also on the physical significance of its parameters. While these parameters are widely used to characterize filler–matrix interactions, in the present study, they were also employed to establish a link with FDM processing conditions. The parameters are summarized in Table 1, and the governing Eq. 5 is expressed as follows:

Table 1 Cross-model parameters of the samples

Sample	η_0 (Pa·s)	k (s)	n	R^2
PB	1396.96	0.0654	0.5797	0.9993
10 NiC	823.543	0.0639	0.5854	0.9989
20 NiC	1044.53	0.0616	0.5333	0.9986
30 NiC	1108.09	0.1029	0.6144	0.9992
40 NiC	1279.86	0.029	0.360	0.9992
50 NiC	1786.75	2.0918	0.3802	0.9977
60 NiC	10476.4	15.6514	0.4269	0.9982

$$\eta(\dot{\gamma}) = \frac{\eta_0}{1 + (k\dot{\gamma})^n}, \quad (5)$$

where $\eta(\dot{\gamma})$ is the apparent viscosity (Pa·s) at a given shear rate $\dot{\gamma}$ (s^{-1}), describing the instantaneous flow resistance of the material under deformation. η_0 is the zero-shear viscosity (Pa·s), representing the material's viscosity in the limit of vanishing shear rate and providing a measure of melt elasticity and structural resistance at rest; in FDM, higher η_0 values are desirable to prevent filament sagging and preserve geometric fidelity. k (s) is the consistency index, inversely proportional to the critical shear rate at which the material departs from Newtonian behavior; larger k values imply a delayed onset of shear thinning and suggest increased resistance to flow initiation inside the nozzle. n is the flow behavior index (dimensionless), indicating the steepness of the shear-thinning transition; lower n values are favorable for FDM as they promote easier flow at high shear rates, but should be interpreted alongside η_0 to ensure that flowability does not compromise post-deposition stability.

All fits yielded high correlation coefficients ($R^2 > 0.99$), confirming that the Cross model adequately captured the viscosity, shear-rate behavior across all filler loadings. As previously discussed, the non-monotonic variation in η_0 with increasing NiC content reflects complex filler–matrix dynamics. Specifically, up to 40 wt% filler, the disruption of polymer–polymer entanglements by NiC particles led to reduced η_0 values, suggesting diminished melt strength under low-shear conditions. Building upon this, the 50 NiC and especially 60 NiC formulations show a sharp rise in η_0 , indicative of a transition to a more percolated and interconnected microstructure that constrains chain mobility. From an FDM processing perspective, such high η_0 values are advantageous, as they improve the extrudate's resistance to deformation before solidification, thereby supporting layer shape retention and geometrical fidelity. Although lower η_0 values in the 10–40 NiC samples point to increased risk of filament sagging or dimensional collapse, these issues may still be manageable through thermal control strategies. For example, elevated cooling fan speeds or enhanced air convection can accelerate post-deposition solidification, partially compensating for inadequate melt strength and helping preserve printed geometry even in low-viscosity systems. The consistency index (k) showed a distinct two-stage trend across the NiC-loaded systems (Table 1). Importantly,

the steady-shear window investigated here directly overlaps with the shear-rate regime ($\approx 10^2$ – 10^3 s^{-1}) experienced by polymer melts during FDM extrusion through the nozzle, as reported in previous processing–rheology studies [25]. This correspondence allows the flow parameters extracted from the Cross model to be interpreted in terms of practical printability. Such a rheology-guided interpretation of extrusion reliability and microstructural stability during FDM processing has also been emphasized in recent studies on FDM-fabricated microwave absorbers and conductive composites [26, 27]. Accordingly, the printability-related implications discussed in this section are inferred from steady-shear behavior and are intended to describe flow initiation inside the nozzle and shape retention immediately after deposition. In the 10–40 NiC range, k values remained relatively low and stable, suggesting that the systems enter the shear-thinning region with minimal structural resistance. This behavior is consistent with the lack of extensive filler–filler networking and highlights the dominance of matrix flow characteristics. In this regime, the low k facilitates easy flow initiation under low-to-moderate shear, which is advantageous for smooth extrusion but may reduce shape stability immediately after deposition. A sharp increase in k was observed for 50 and 60 NiC formulations, indicating the formation of microstructures that resist deformation until higher shear levels are applied. This jump in k implies that stronger internal resistance exists in these systems, likely due to partial or full percolation, and that more shear energy is required to trigger structural rearrangements. For FDM applications, such behavior may enhance dimensional control and reduce filament collapse under gravity, as the melt remains more resistant to flow until directed deformation occurs. However, this benefit may come at the cost of slightly increased extrusion pressure requirements. The n values exhibited relatively minor variations across the investigated formulations, indicating no significant alteration in the overall shear-thinning character. For 0–30 NiC, n remained in the narrow range of 0.53–0.61, suggesting that the flow behavior was primarily governed by the matrix, with negligible disruption from the filler. At 40 NiC, a moderate reduction in n (≈ 0.36) was observed, followed by a slight increase at higher loadings (50 NiC: 0.38, 60 NiC: 0.43). This pattern does not reflect a sharp transition but rather a subtle evolution, possibly linked to the onset and stabilization of filler networks. Overall, the absence of a distinct trend in n supports

the conclusion that filler addition influenced the magnitude of viscosity (i.e., η_0 and k) more significantly than the shear-thinning exponent itself.

3.2 Thermomechanical behavior and FDM process implications

DMA was conducted to investigate the solid-state microstructure and the temperature-dependent elastic response of PB/NiC composites. The variation of E' with temperature, obtained from DMA measurements, is presented in Fig. 2a. The unfilled PB matrix exhibits a nearly constant E' up to $\sim 60^\circ\text{C}$, in agreement with the expected T_g of PLA. This behavior confirms that the thermomechanical response in the glassy region is dominated by the PLA phase, which remains structurally rigid until its segmental motion is thermally activated near T_g . In contrast, all NiC-filled composites demonstrate an earlier onset of modulus decay, with the critical temperature dropping to $\sim 45^\circ\text{C}$ regardless of filler content. While such a trend may suggest a depression of T_g , this interpretation is not supported by classical thermodynamics or known filler effects in

PLA systems [28]. Instead, the observed shift arises from the mechanics of dynamic loading. Unlike calorimetric techniques, DMA continuously subjects the specimen to oscillatory deformation, making it sensitive to interfacial slippage and local structural instabilities. In this context, the earlier E' drop in composites can be ascribed to weak filler–matrix interactions, as previously indicated by rheological flow behavior. The presence of NiC, especially in systems with low-to-moderate filler content, disrupts chain continuity without providing sufficient interfacial adhesion to resist applied stress. This leads to localized softening under dynamic load, manifesting as an apparent modulus loss at sub- T_g temperatures. Importantly, this should not be misconstrued as a reduction in the intrinsic T_g of the polymer, but rather as a mechanically induced early relaxation driven by poor interfacial integrity. In the temperature range beyond the T_g of PLA, the unfilled PB blend exhibits a distinctive increase in E' starting around 80°C , which is a well-known characteristic of cold crystallization [29]. This behavior is commonly observed in semi-crystalline PLA-based systems, where the amorphous chains gain mobility upon heating and begin to reorganize into ordered crystalline domains. Although the presence of TPU somewhat suppresses this recrystallization process due to phase mixing and reduced chain mobility, the relatively low TPU content in this blend allows the PLA phase to retain its ability to crystallize upon heating. As a result, a clear modulus increase is observed up to approximately 110°C , beyond which thermal softening and melting of the newly formed crystallites lead to sample failure. In contrast, the NiC-filled composites do not display a comparable modulus recovery in this temperature region. Despite the similar PLA content across all formulations, the interfacial incompatibility between the filler and the matrix appears to hinder the development of a coherent crystalline structure capable of supporting the applied oscillatory stress. Consequently, the cold crystallization phenomenon is largely suppressed, and the samples tend to lose mechanical integrity at significantly lower temperatures. This outcome further highlights the detrimental effect of weak filler–polymer interactions, which limit not only stress transfer efficiency but also the structural evolution during dynamic heating.

Within the glassy region, which corresponds to typical service temperatures for PLA-based materials, the incorporation of NiC resulted in a progressive enhancement in E' with increasing filler content.

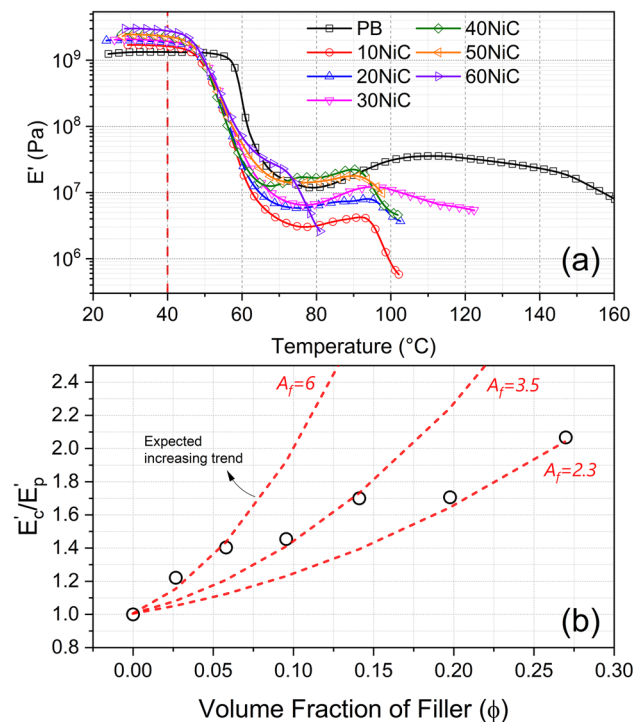


Fig. 2 **a** Temperature-dependent variation of E' for PB composites with varying NiC content. **b** Relative modulus values plotted as a function of ϕ , along with theoretical curves fitted using the modified Guth model

Contrary to the behavior observed in the melt state, where poor interfacial adhesion undermines mechanical reinforcement, here the rigid nature of the filler contributes significantly to the overall stiffness of the system. The observed increase in E' is consistent across the 10–60 wt% filler range and indicates that, despite limited chemical compatibility, stress transfer is adequately maintained at low temperatures due to the inherently stiff NiC structure. To provide a more quantitative understanding of this reinforcement, the relative modulus, defined as the ratio of the composite storage modulus to that of the neat polymer (E'_c/E'_p), was plotted as a function of filler volume fraction (ϕ), as shown in Fig. 2b. This representation facilitates further evaluation of the dispersion quality and aspect ratio (A_f) of the filler particles, which are key factors governing mechanical performance in composite systems. In this context, the modified Guth model was employed to fit the data and extract the effective A_f values [30]. Contrary to the typical exponential or superlinear increase in stiffness expected with rising filler content, the E' values in this study do not follow a monotonic or continuously accelerating trend. As shown in Fig. 2b, the addition of 10 and 20 NiC resulted in an increase in E' that is broadly consistent with literature-reported reinforcement behavior [31], suggesting acceptable filler dispersion and interfacial stress transfer at low loadings. However, beyond this range, the mechanical response deviates from the expected pattern: both 30 and 40 wt% composites exhibit lower-than-expected increases in E' , and this deviation becomes even more pronounced at 50 and 60 wt%, where the reinforcement efficiency significantly deteriorates. These observations point toward a deterioration in dispersion quality and a loss of filler effectiveness at higher concentrations, most likely due to agglomeration and weakened interfacial adhesion. To gain quantitative insight into these deviations, the modified Guth equation was applied to the relative modulus (E'/E'_0) as a function of filler volume fraction (ϕ):

$$\frac{E_c}{E_m} = 1 + 0.67\phi \cdot A_f + 1.62\phi^2 \cdot A_f^2 \quad (6)$$

Here, A_f represents the effective aspect ratio of the filler. The model curves fitted with different A_f values are also plotted in Fig. 2b. Notably, no single A_f value could capture the full experimental trend. For the low filler content range (10–20 wt%), the best fit

was obtained with $A_f \approx 6$, suggesting well-dispersed and elongated filler morphology. In contrast, the intermediate range (30–40 wt%) aligned with a reduced $A_f \approx 3.5$, and at the highest loadings (50–60 wt%), the data could only be described by a further lowered $A_f \approx 2.3$. This progressive decline in apparent A_f reflects a deterioration in dispersion quality and an increase in filler–filler interactions that compromise reinforcement efficiency.

From an FDM processing standpoint, the observed reduction in the critical temperature at which E' begins to decrease may have practical implications for cooling dynamics. Although this shift does not indicate a true decrease in T_g , it suggests that the material starts to lose stiffness at slightly lower temperatures. In this context, effective cooling becomes more important to ensure that each extruded layer rapidly solidifies and maintains its shape fidelity, especially for geometrically complex or unsupported regions. Thus, appropriate fan control and cooling rate adjustments may help stabilize interlayer bonding and prevent deformation during printing. Lastly, the enhancement of E' values within the glassy region across increasing NiC loadings confirms that mechanical rigidity is retained or improved under service conditions, making these composites suitable for applications requiring higher stiffness at ambient or moderately elevated temperatures.

3.3 Dielectric properties

The frequency-dependent behaviors of ϵ' , ϵ'' , μ' , and μ'' , along with the dielectric loss tangent (ϵ''/ϵ') and magnetic loss tangent (μ''/μ'), of the compression-molded (CM) composite samples are presented in Fig. 3a–f. Figure 3a presents the variation of ϵ' , which reflects the ability of a material to store electrical energy through polarization under an alternating electric field. In polymer-based composites, ϵ' is primarily governed by interfacial polarization mechanisms, particularly at the interfaces between the polymer matrix and conductive fillers. The incorporation of NiC leads to the formation of microcapacitor-like structures, where the conductive NiC particles act as electrodes, and the surrounding polymer serves as the insulating medium. As the filler content increases, the number of such microcapacitor units rises, while the thickness of the dielectric (polymer) phase between adjacent fillers decreases. This dual effect enhances the interfacial polarization capacity of the system,

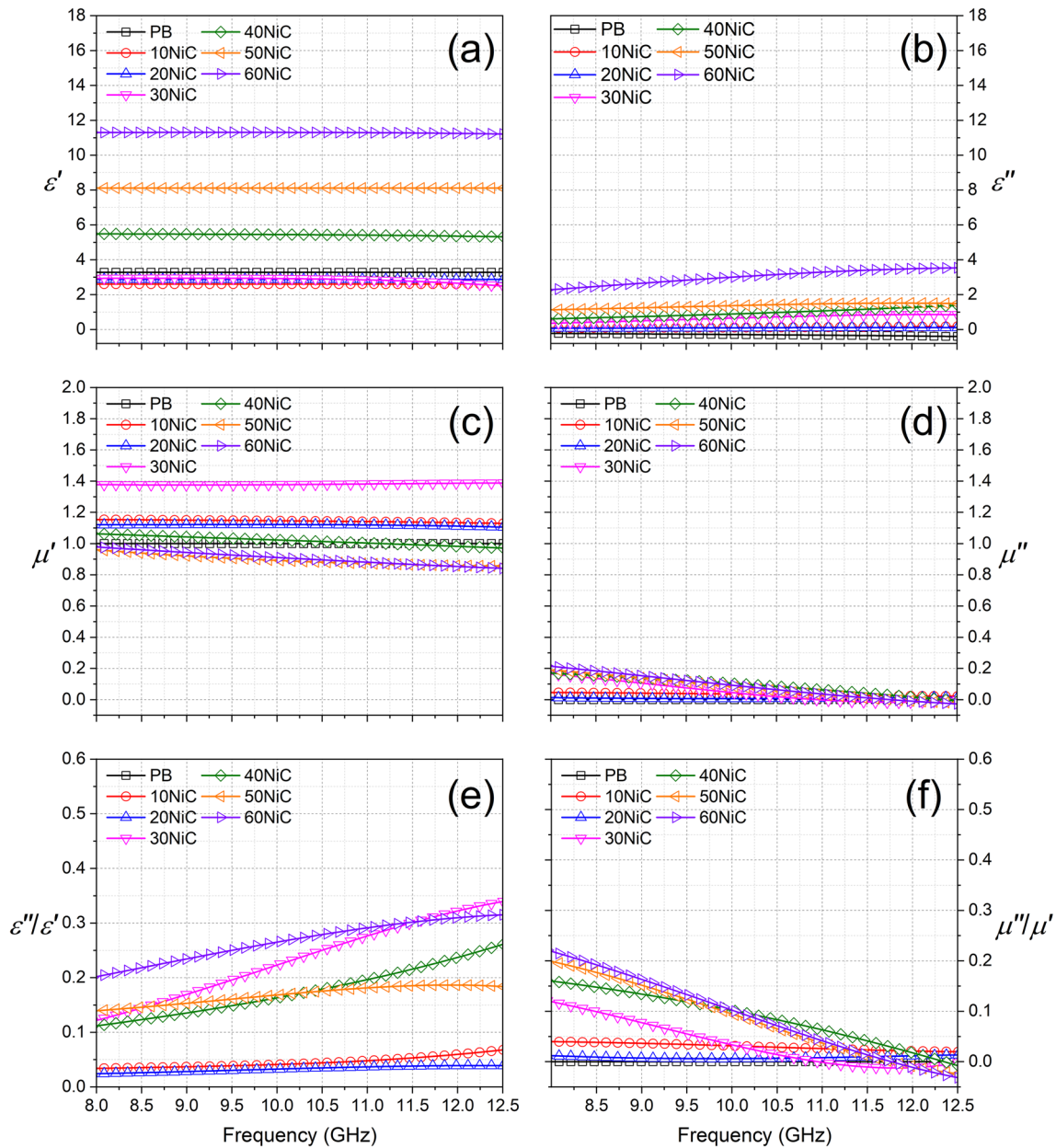


Fig. 3 **a** ϵ' , **b** ϵ'' , **c** μ' , **d** μ'' , **e** ϵ''/ϵ' , and **f** μ''/μ' values of the composite samples

resulting in a steady increase in ϵ' values with increasing NiC loading. This trend is consistent with classical dielectric theory and has been widely observed in heterogeneous systems with conductive fillers dispersed in insulating matrices [32]. As shown in Fig. 3a, the samples containing 0, 20, and 30 wt% NiC exhibit ϵ' values that remain consistently lower than that of the neat polymer across the entire frequency range. This indicates that at these relatively low filler loadings, the formation of NiC | polymer | NiC microcapacitor

structures is not sufficient to enhance the dielectric response. However, this insufficiency is likely not due to the number of conductive particles alone, but rather the excessive thickness of the intervening polymer phase. When the dielectric layer becomes too thick, the electric field cannot effectively polarize the polymer chains across adjacent filler particles, thereby weakening interfacial polarization. Additionally, such large insulating domains may disrupt the internal polarization equilibrium of the polymer matrix itself,

leading to suppressed ϵ' values. This phenomenon has also been reported in the literature, where overly thick dielectric layers reduce the local field strength and limit dipole alignment efficiency [33]. At 40, 50, and 60 wt% NiC contents, ϵ' shows a nearly linear increase with filler volume fraction, as shown in Fig. 3a. This behavior is attributed to the formation of more NiC | polymer | NiC microcapacitor structures and the thinning of the polymer layer between particles, which together enhance interfacial polarization. The linear trend suggests that filler particles are added in a relatively uniform manner, providing consistent contribution to dielectric storage without yet causing conductive losses.

The imaginary part of the permittivity (ϵ''), shown in Fig. 3b, represents the material's capacity to dissipate electrical energy and is primarily linked to interfacial polarization and conductive losses. In polymer composites filled with conductive particles, ϵ'' becomes increasingly sensitive to filler–filler contact as the filler content rises. Up to 50 wt% NiC, ϵ'' values remain relatively low across the frequency range, suggesting that charge transport is still dominated by isolated microcapacitor structures with limited interparticle connectivity. However, at 60 wt%, ϵ'' increases sharply, indicating the formation of extended conductive networks—consistent with the percolation behavior observed in rheological data. This increase in ϵ'' can be associated with the emergence of effective filler–filler contact paths, which facilitate hopping or tunneling mechanisms of charge transport. Importantly, the AC conductivity (σ_{ac}) can be estimated using the classical relation:

$$\sigma_{ac} = 2\pi f \epsilon_0 \epsilon'' \quad (7)$$

Assuming representative values of ϵ'' and operating frequency in the X-band (8.0–12 GHz), the resulting conductivity remains in the order of ~ 1 S/cm. While this value would be considered high in low-frequency or DC regimes, it is still relatively low in the context of microwave frequencies. Therefore, the system does not behave as a true conductor and does not reflect incident electromagnetic waves significantly. Instead, it acts as a lossy dielectric material capable of attenuating microwave energy via absorption rather than reflection—consistent with its intended function in radar-absorbing applications.

Following the analysis of dielectric behavior, the magnetic response of the composites is presented

in Fig. 3c and d. μ' reflects the material's capacity to store magnetic energy, while μ'' corresponds to magnetic loss mechanisms such as domain wall motion, spin relaxation, and eddy-current dissipation. For the neat polymer matrix, μ' remains near unity and μ'' is nearly zero throughout the X-band, as expected from a non-magnetic baseline. With the incorporation of NiC fillers, a moderate increase in μ' is observed at intermediate ϕ , but μ' subsequently declines as ϕ further increases. For Ni-coated carbon, this behavior can be rationalized by the thin-shell architecture and rising electrical continuity at high ϕ : eddy-current screening in the Ni shell and magnetostatic coupling between neighboring shells generate demagnetizing fields that suppress the net inductive response, thereby lowering μ' in the X-band. In addition, the carbon core is non-magnetic (magnetic dilution), so adding more particles does not proportionally increase the magnetic volume; instead, conductivity-driven effects dominate. Consistent with this picture, μ'' remains low for all compositions and shows only a minor low-frequency uptick at the highest ϕ , attributable to contact-enabled eddy currents within the interconnected filler structure, a secondary loss channel compared with the dielectric contribution.

The dielectric and magnetic loss tangents, expressed as ϵ''/ϵ' and μ''/μ' , respectively, serve as crucial indicators of the energy dissipation capacity of a material under alternating electromagnetic fields. Higher values of these ratios generally imply enhanced intrinsic attenuation capability, which is highly desirable in microwave absorption applications. As shown in Fig. 3e, the dielectric loss tangent (ϵ''/ϵ') exhibits a consistent upward trend across the frequency range of 8.0–12 GHz for all samples, indicating frequency-enhanced dielectric dissipation. Moreover, increasing the filler content leads to a monotonic rise in ϵ''/ϵ' , with the 50 and 60 NiC samples clearly forming the uppermost band. Intermediate compositions (30 and 40 NiC) show closely overlapping behavior, particularly in the lower-frequency region, where slight inversions occur due to differential contributions from ϵ' and ϵ'' . This overall pattern suggests that the dielectric losses are governed primarily by interfacial polarization (Maxwell–Wagner–Sillars effect) and increasingly by conduction-related loss mechanisms as the filler content approaches the percolation threshold. In contrast, the magnetic loss tangent (μ''/μ') shown in Fig. 3f displays a decreasing trend with frequency for all compositions, accompanied by a convergence behavior at

higher frequencies. At the lower end of the frequency spectrum, a weak but discernible increase in μ''/μ' with rising ϕ is observed, with 60 NiC showing the highest magnetic loss response. Nonetheless, the overall magnitude of μ''/μ' remains relatively low throughout the measured frequency range. This finding indicates that magnetic loss contributions are secondary to dielectric mechanisms in the present system, and dielectric dissipation is the dominant mode of electromagnetic energy attenuation.

3.4 Microwave absorption performance

As a baseline reference, CM composites were first evaluated to establish the effect of filler loading independent of printing architecture. In this context, the hot-pressing technique was deliberately chosen to eliminate the influence of 3D printing-induced factors such as interlayer voids, directional anisotropy, and incomplete fusion between successive filaments. By utilizing a compression-molding route, a dense and uniform microstructure was obtained, free from geometrical artifacts inherent to fused deposition modeling (FDM) processes.

The microwave absorption performance of the samples was analyzed using two-dimensional RL contour maps as functions of frequency and absorber thickness (Fig. 4). Yellow regions correspond to weak attenuation (-5 to 0 dB), whereas green-to-dark zones denote effective absorption ($RL \leq -10$ dB), which is the conventional threshold for practical applications. Composites with 10–30 wt% NiC exhibited RL values consistently above -5 dB, confirming insufficient attenuation capacity. This limitation is attributed to weak interfacial polarization and the absence of conductive pathways, in agreement with rheological and dielectric results that indicated poor filler–filler interactions and low permittivity in this range. At 40 wt% NiC (Fig. 4a), RL values were confined to -5 to 0 dB. For the 50 NiC composite (Fig. 4b), a localized absorption zone was detected in the lower X-band ($f \approx 8.0$ – 9.5 GHz, $t \approx 2.3$ – 3.2 mm), reaching a minimum RL of approximately -10 dB. This response reflects the partial establishment of local NiC networks, corroborated by rheological and dielectric analyses. By contrast, the 60 NiC sample (Fig. 4c) exhibited markedly improved performance, including a deep absorption minimum near -20 dB at $f \approx 8.0$ – 8.5 GHz ($t \approx 2$ mm) and a secondary absorption region at $f \approx 10.5$ – 11.5 GHz ($t \approx 1.3$ – 1.8 mm) with RL values between -12 and -17 dB.

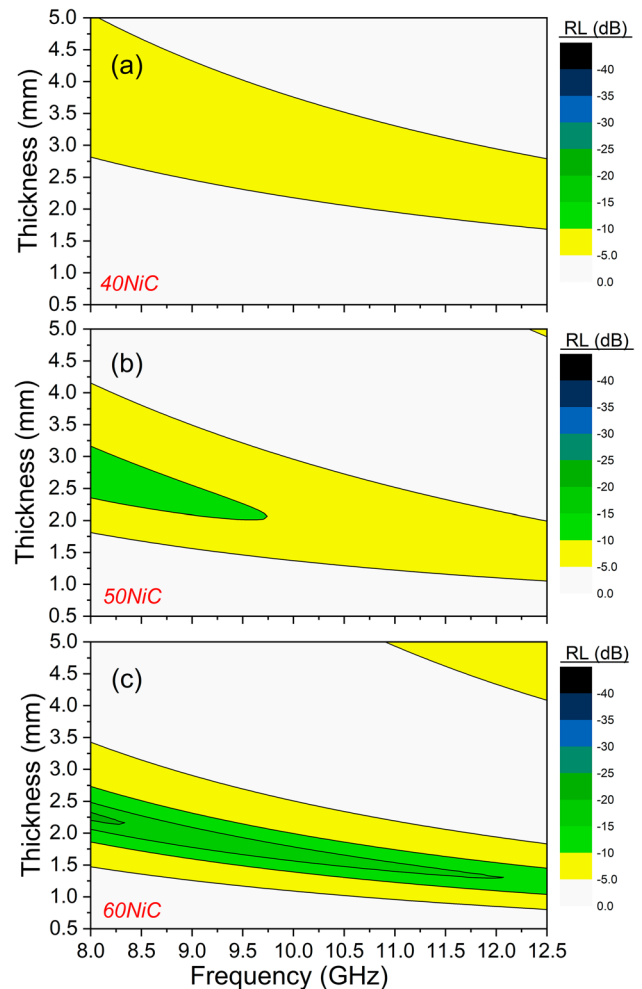


Fig. 4 Contour maps of **a** 40 NiC, **b** 50 NiC, and **c** 60 NiC samples

3.5 Evaluation of infill architectures in 3D-printed structures

In earlier stages of this study, the PB blend containing 60 wt% NiC was identified as the optimal formulation based on its overall thermal, mechanical, dielectric, and microwave absorption properties when prepared via compression molding. However, the transition from bulk processing to FDM introduces additional complexity due to the geometric characteristics of the printed structure. Even when a nominal 100% infill is selected, the internal patterning dictated by slicing strategies, such as Concentric, Grid, or Cubic Subdivision, results in variations in the actual material density and internal architecture. These variations significantly affect not only the mechanical and thermal stability of the printed parts but also their dielectric

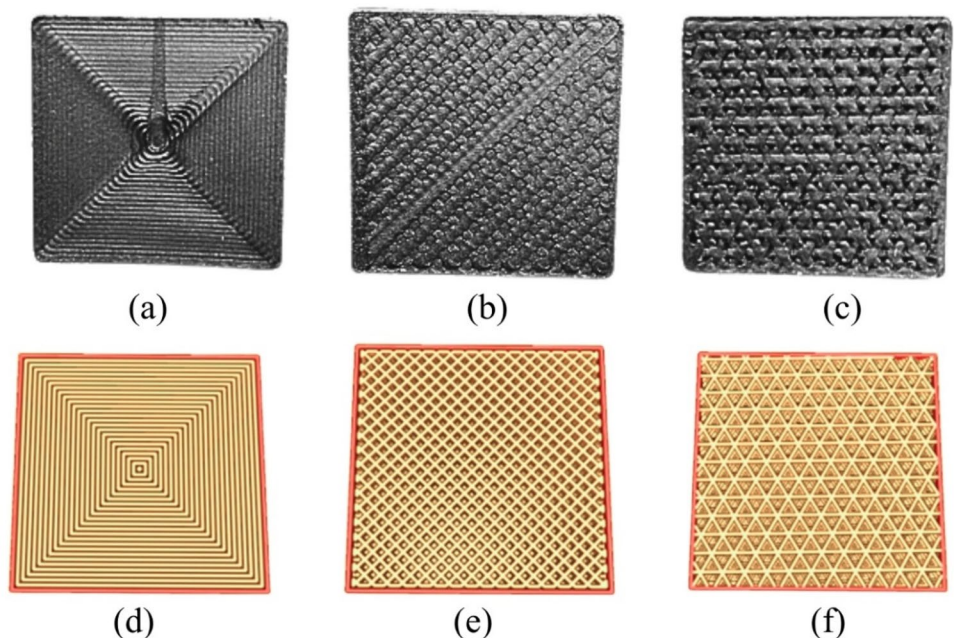
behavior and microwave attenuation performance. To explore this effect, the previously optimized 60 NiC formulation was processed via FDM using different infill geometries. A preliminary screening was performed on nearly ten distinct infill types, and their bulk densities were measured. Among them, three patterns, Concentric, Grid, and Cubic Subdivision, exhibited clearly distinguishable density profiles, measured as 1.92, 1.83, and 1.63 g/cm³, respectively. For comparison, the density of the CM sample was measured to be approximately 2.10 g/cm³. These patterns were therefore selected for further comparative analysis. Figure 5 presents the schematic toolpath visualizations and the corresponding photographs of the FDM-printed parts for the three infill types.

Figure 6 presents the dielectric and magnetic parameters of the composite samples prepared by different infill methods. For comparison purposes, the corresponding properties of the compression-molded sample are also included as a reference. Despite using identical composite formulations (60 NiC), the electromagnetic response of the samples significantly varies depending on the applied manufacturing strategy.

Among the different FDM-based infill patterns, the concentric design yields the highest ϵ' and ϵ'' values. This enhancement originates from the continuous and circular toolpath architecture, which introduces numerous filament–filament interfaces and extended conduction paths. Such microstructural arrangement

intensifies interfacial polarization (Maxwell–Wagner–Sillars) and conductive losses, leading to superior dielectric characteristics. CM samples, though exhibiting the highest physical density ($\rho \approx 2.1$ g cm⁻³), do not outperform concentric samples in terms of dielectric parameters. The limited number of internal interfaces and homogeneous morphology reduce interfacial contributions, resulting in lower ϵ' and ϵ'' than expected. Interestingly, Grid-patterned FDM samples, with intermediate density, show dielectric properties comparable to CM ones. Their advantage stems from a higher interfacial area and partially aligned conduction paths, partially compensating for their lower ρ . Cubic Subdivision samples demonstrate the lowest ϵ' and ϵ'' values across the set, mainly due to their low density ($\rho \approx 1.63$ g cm⁻³) and highly discontinuous internal architecture. The sparse and disconnected filament network suppresses both interfacial polarization and electrical conduction, making this design the least effective for electromagnetic absorption. On the other hand, across the measured frequency range, the CM sample consistently shows the lowest values of both μ' and μ'' . These results can plausibly be attributed to its interface-poor, well-wetted morphology, which may increase the average spacing between NiC particles and reduce direct interparticle contacts. Such a structure is likely to weaken exchange and dipolar interactions, thereby limiting the in-phase permeability μ' . Similarly, the relatively compact and isotropic

Fig. 5 Photographs (a–c) and slicing previews (d–f) of 3D-printed 60 NiC composite samples in the order: concentric, grid, and cubic subdivision



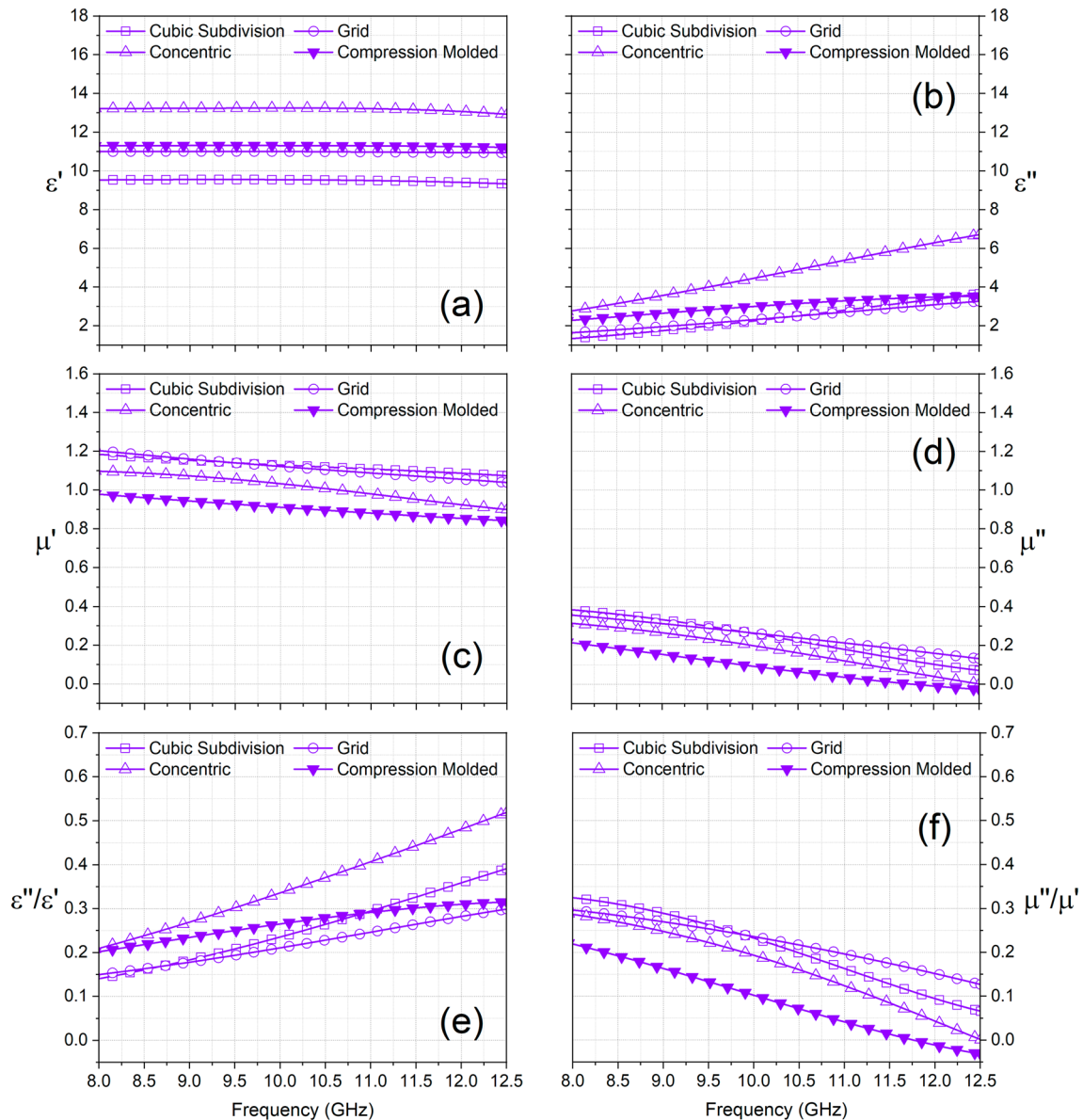


Fig. 6 Electromagnetic parameters of 60 NiC-PLA composites with different infill patterns: **a** ϵ' , **b** ϵ'' , **c** μ' , **d** μ'' , **e** ϵ''/ϵ' , and **f** μ''/μ'

packing in CM might restrict the formation of closed conductive loops, keeping the effective conductivity modest and suppressing eddy-current losses, reflected in lower μ'' values. The absence of pronounced interfacial regions could also limit MWS-type magnetic relaxation mechanisms. Furthermore, the geometrical arrangement may enhance demagnetizing fields due to less cooperative particle alignment, leading to a further reduction in internal magnetic response. In contrast, the three FDM-based structures yield generally higher μ' and μ'' values, possibly due to greater interfacial complexity and local connectivity, which

could facilitate stronger coupling effects, even though the magnetic filler content remains identical. Across the measured frequency range, ϵ''/ϵ' of the CM specimen remains at an intermediate level, generally lower than the Concentric pattern, comparable to Grid, and above Cubic. In contrast, μ''/μ' is consistently the lowest among all samples. This trend suggests that, while the compression-molded morphology may sustain moderate dielectric dissipation comparable to certain FDM patterns, it provides only limited magnetic loss compared with the printed architectures. The three FDM-based designs, despite their different internal

geometries, show higher μ''/μ' values, with the typical order Cubic > Grid > Concentric, indicating that magnetic loss behavior is more sensitive to infill-induced microstructure than dielectric loss behavior.

The microwave absorption performance of the 60 NiC composites with different infill architectures was systematically examined over the X-band (8.0–12.5 GHz), as shown by the *RL* contour plots in Fig. 7. Figure 7a–d represents Cubic Subdivision, Grid, Concentric, and Compression Molding (CM), respectively. Across the X-band, all four samples display a continuous –10 dB absorption band, with the required thickness decreasing as frequency increases. Among them, the CM specimen exhibits the broadest and deepest attenuation window, including extended regions below –15 dB. Notably, the Concentric infill architecture demonstrates a performance remarkably close to CM, offering a comparable –10 dB coverage and similar minimum reflection levels. The Grid and Cubic designs also yield functional absorption, though the former presents a narrower and partially fragmented band, while the latter requires greater thickness to reach the –10 dB threshold. These findings suggest that Concentric may serve as the most promising 3D-printed alternative to compression molding for broadband microwave attenuation, particularly

within the practical thickness range of 1.5–2.0 mm. Notably, the concentric infill architecture exhibited comparable—and in certain thickness and frequency ranges, locally improved—attenuation behavior relative to the fully dense compression-molded references, indicating that strategic shear-induced alignment and enhanced packing continuity can effectively compensate for the inherent micro-porosity of the FDM process [6, 27]. The observed performance of the concentric infill architecture suggests a synergistic process–structure–performance relationship. While compression-molded specimens provide maximum material density, their largely random filler distribution may limit the efficiency of conductive network formation. In contrast, the FDM-printed concentric toolpaths promote shear-induced alignment of NiC fillers along the deposition direction, facilitating the formation of spatially continuous and preferentially oriented conductive pathways that interact more effectively with incident electromagnetic waves [34].

3.6 Performance optimization through pyramidal designs

To validate the predictive accuracy of the dielectric-parameter-based calculations, the *RL* obtained from

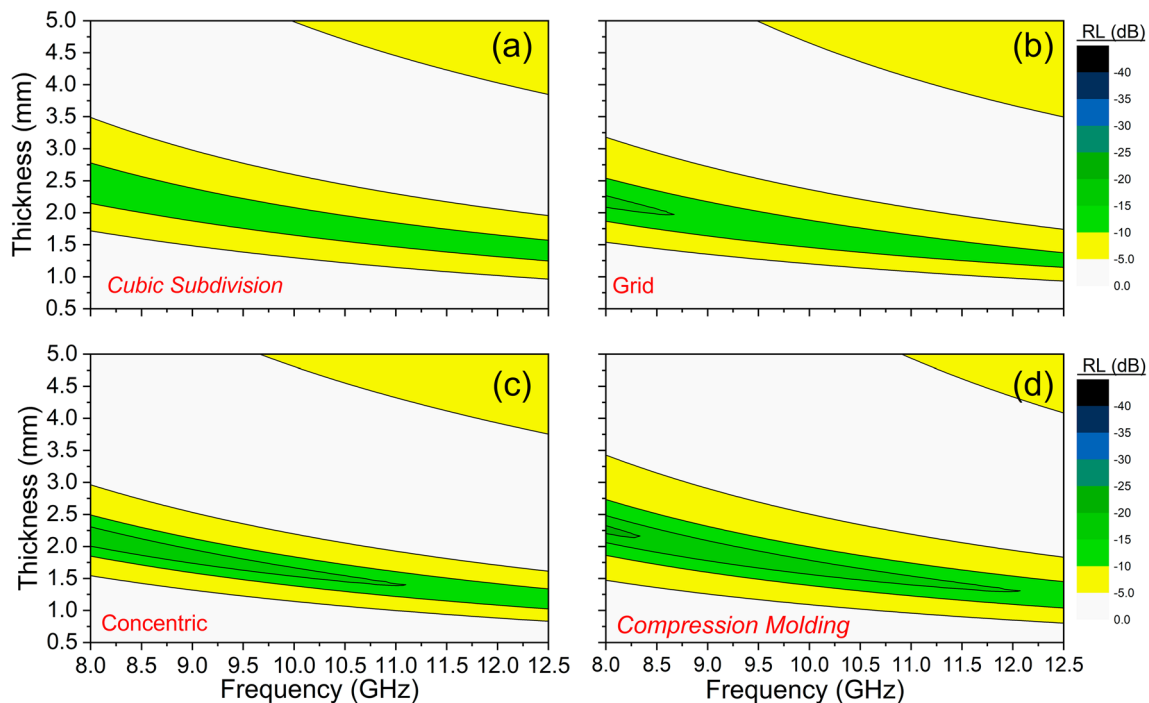


Fig. 7 Contour maps of 60 NiC composites fabricated by four different processing methods: **a** cubic subdivision, **b** grid, **c** concentric, and **d** compression molding

coaxial airline measurements was directly compared with the RL measured by the free-space method. For this purpose, the same 60 NiC composite fabricated using the concentric infill strategy was evaluated in two formats: (i) a small coupon cut from the printed panel and tested in a coaxial airline fixture, where a thickness of approximately 1.6 mm was used in the calculations; and (ii) a full-size $100 \times 100 \times 1.6$ mm plate measured under free-space conditions. Figure 8a presents the resulting RL spectra from both approaches, enabling a direct assessment of how the calculated (coaxial) and measured (free-space) responses of the same material compare across the X-band. As illustrated in Fig. 8a, the RL spectra obtained from the free-space and coaxial measurements exhibit a high degree of consistency across the X-band. In both cases, the -10 dB threshold is crossed near 8.5–9.0 GHz and maintained until approximately 10.5–11.0 GHz, defining a comparable effective absorption bandwidth. Furthermore, both methods yield a minimum RL value close to -15 dB, indicating that the intrinsic microwave attenuation capability of the concentric-infill 60 NiC composite is reliably captured by both measurement techniques.

One of the major advantages of preparing 3D-printable filaments is the ability to fabricate complex geometries with high precision and design flexibility. This capability can be strategically exploited to enhance microwave attenuation by tailoring the absorber's shape and surface features. In order to elucidate the influence of geometry on the electromagnetic absorption behavior of NiC-based composites, pyramidal

structures were selected due to their well-established capability to provide a gradual impedance transition between free space and lossy media [35, 36]. By jointly considering pyramidal geometry and the intrinsic dielectric loss characteristics of the NiC composite, the effect of structural unit size on absorption performance was systematically examined under controlled material and processing conditions. To primarily emphasize geometry-driven effects while minimizing material-related variations, the structural design was partitioned into a fixed lateral base dimension and variable pyramid heights. The lateral unit cell dimension was fixed at 20×20 mm to satisfy the sub-wavelength condition across the entire X-band (8.2–12.4 GHz). Given that the free-space wavelength (λ_0) in this frequency range varies approximately between 24.2 and 36.5 mm, maintaining a periodicity smaller than the minimum wavelength promotes homogenized electromagnetic behavior and suppresses diffraction-related contributions [37]. In addition, the role of the 20-mm pyramid height in enabling a progressive electromagnetic transition between free space and the lossy composite medium is now discussed, highlighting the synergistic interaction between geometry and material loss mechanisms.

In this context, the present study investigated the integration of pyramidal structures, widely recognized for their broadband absorption performance, onto composite substrates. Three different pyramid-based absorber designs were fabricated using a fixed base size of 20×20 mm², while varying the height to 10, 20, and 30 mm to study the influence of vertical dimension

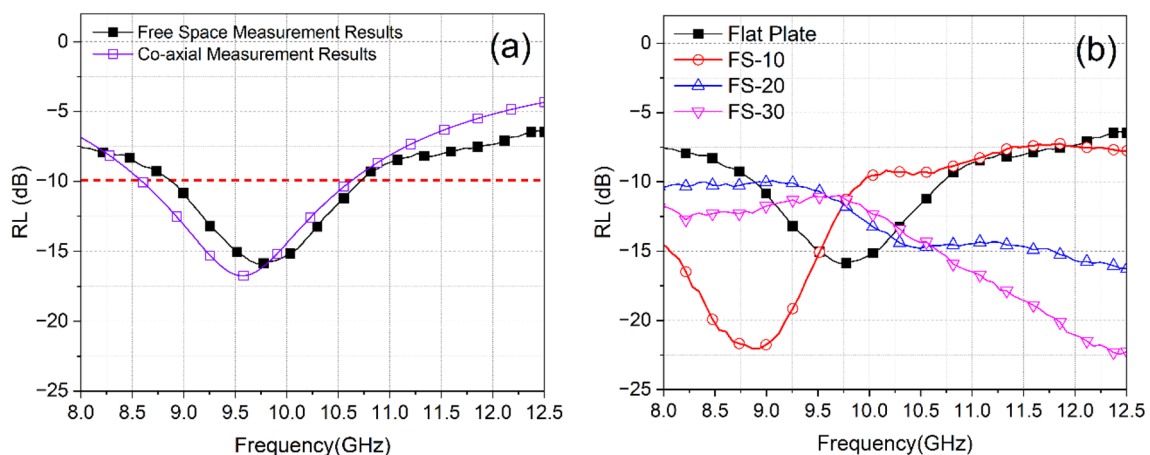
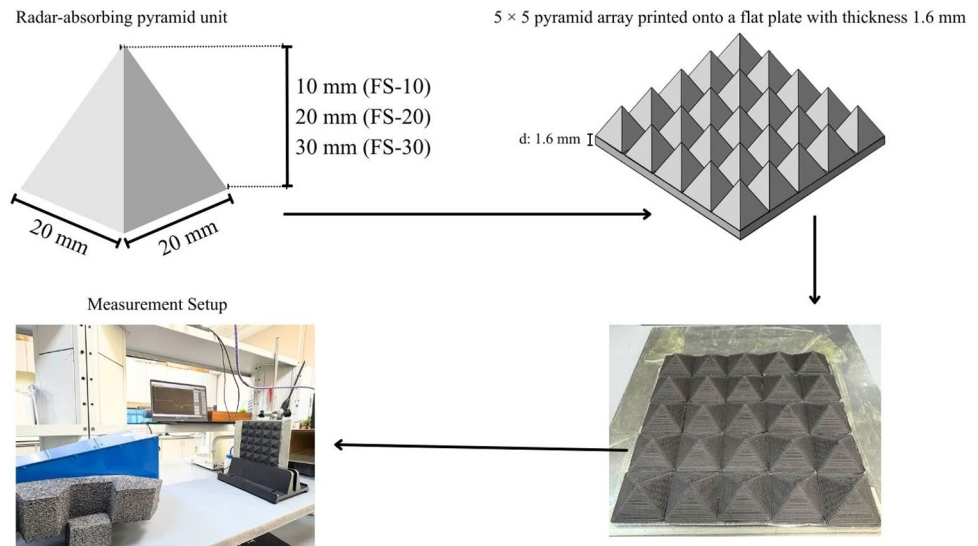


Fig. 8 **a** Comparison of RL values obtained by free-space and coaxial measurement techniques. **b** RL performance of different pyramidal designs

Fig. 9 Schematic representation and experimental validation of radar-absorbing pyramid arrays



on electromagnetic performance. Each configuration was arrayed across a $100 \times 100 \times 1.6$ mm flat plate, yielding periodic and uniformly distributed structures suitable for free-space testing. The three designs were coded as FS-10, FS-20, and FS-30, respectively, where the numerical label corresponds to the pyramid height in millimeters. Visual representations of the fabricated test specimens corresponding to the FS-10, FS-20, and FS-30 configurations are provided in Fig. 9. In parallel, the pyramid height was identified as a critical parameter governing the geometric transition of effective electromagnetic response between free space ($Z_0 \approx 377 \Omega$) and the lossy composite medium. A parametric investigation involving three different heights (10, 20, and 30 mm) was conducted to identify a suitable geometric transition profile that facilitates effective penetration of incident electromagnetic waves into the high-loss NiC matrix. While a height of 10 mm was insufficient to provide adequate geometric modulation of effective electromagnetic response and resulted in premature surface reflection, the 20-mm height (FS-20) established a smoother transition profile, consistent with reported optimization approaches based on height-to-base aspect ratios for pyramidal absorbers. Microwave attenuation performance of the 3D-printed pyramidal structures is presented in Fig. 8b. Among the tested configurations, FS-20 clearly stands out by maintaining $RL < -10$ dB across nearly the entire X-band (9.0–12.5 GHz), reaching a minimum RL of approximately -15 dB. This performance indicates that FS-20 is the most suitable single geometry for achieving

broadband absorption. In contrast, FS-10 provides strong attenuation only in the lower X-band region (~ 8.3 – 9.6 GHz), with a sharp dip around -20 dB, but its effectiveness rapidly diminishes beyond 9.8 GHz, limiting its usability for broadband applications. On the other hand, FS-30 demonstrates improved performance in the upper X-band (10.0–12.5 GHz), exhibiting a deep minimum (~ -20 dB) around 10.8–11.2 GHz, but fails to achieve -10 dB RL below 9.5 GHz, making it less effective in the lower-frequency range. These results suggest that FS-10 and FS-30 act as complementary geometries, targeting different sections of the X-band, while FS-20 uniquely fulfills the full-band -10 dB criterion on its own.

3.7 Lightweighting via infill ratio control in pyramidal structures

To reduce the total mass of the absorber system while preserving electromagnetic performance, FS-20 pyramidal absorbers were printed with concentric infill at varying infill ratios and tested in free-space configuration. In each case, the pyramidal structures were mounted over a 1.6-mm-thick flat base plate to ensure consistent boundary conditions. As shown in Fig. 10, decreasing the infill ratio from 100 to 50%, 30%, and ultimately to 0% (shell-only) progressively altered the RL characteristics across the X-band (8.0–12.5 GHz). Among all configurations, the 30% infill structure exhibited the most balanced and efficient performance, achieving

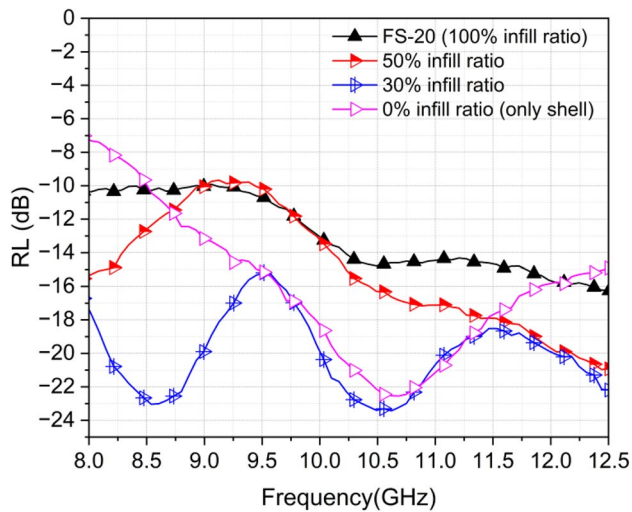


Fig. 10 RL curves of FS-20 pyramidal structures with varying infill ratios (100, 50, 30, and 0%) measured via free-space technique

a $\approx 58\%$ reduction in total mass relative to the fully solid (100%) reference while maintaining broadband absorption with two pronounced minima reaching about -25 dB. This enhancement is attributed to a graded dielectric profile generated along the pyramid height, which promotes smoother impedance transition and stronger internal attenuation. In contrast, the 50% infill structure ($\approx 43\%$ lighter) produced only a modest improvement. The 0% infill (shell-only) design ($\approx 73\%$ lighter) exhibited a slight reduction in absorption efficiency at the lower end of the X-band ($\approx 8\text{--}9$ GHz) but still maintained strong attenuation in the mid-to-upper frequency range ($\approx 10\text{--}12$ GHz), with RL values reaching -16 to -20 dB. Overall, the 30% infill configuration represents the optimum lightweighting condition, combining significant mass reduction with preserved and even enhanced broadband absorption across the X-band.

When compared with the flat 1.6-mm-thick concentric plate serving as the material reference, the FS-20 pyramidal configuration exhibited a substantially broadened effective absorption bandwidth. This improvement originates from the geometry-induced spatial impedance transition introduced by the 20-mm pyramidal profile above the base plate. Moreover, relative to the fully solid pyramidal configuration, the optimized 30% infill design achieved approximately 58% mass reduction while preserving broadband attenuation. This direct experimental

comparison confirms that the observed broadband enhancement does not originate solely from the intrinsic dielectric attenuation of the NiC composite, but rather from geometry-induced impedance grading and progressive electromagnetic transition along the pyramid height. Accordingly, the broadband behavior of the FS-20 pyramidal absorber can be interpreted as a synergistic interaction between geometric transition and intrinsic dielectric loss of the NiC composite. In contrast to the flat plate response, which is primarily governed by intrinsic material attenuation and interference effects, the pyramidal geometry introduces a gradual spatial transition of effective impedance from free space to the lossy medium. This graded transition reduces the initial surface reflection tendency and increases the electromagnetic penetration depth within the structure. As a result, incident waves are progressively attenuated along the pyramid height before reaching the high-density base region, where interfacial polarization and conductive loss mechanisms dominate. This combined geometric–material interaction explains the significantly broadened ~ 10 dB bandwidth observed for FS-20 compared to the flat configuration.

To further facilitate this, the 3D-printed cellular voids within the pyramids were strategically designed to function in a manner analogous to multi-stage energy redistribution mechanisms reported in recent literature [38]. In this configuration, the air-filled void regions act as low-density transition domains that modify the local effective electromagnetic response, allowing incident waves to penetrate deeper into the structure rather than being predominantly reflected at the surface. The stepped void–solid architecture thereby supports a gradual spatial transition of the effective electromagnetic properties along the pyramid height. As the waves propagate inward, energy is progressively attenuated through multiple internal reflections, interfacial polarization, and conductive loss within the NiC-composite skeleton. This structural strategy is consistent with recently reported multiscale absorber architectures [39, 40], where geometric modulation enhances energy coupling and internal dissipation without relying on discrete resonance effects. In this context, the FS-20 configuration can be interpreted as a geometry-assisted broadband attenuation structure. By regulating the interaction between the incident electromagnetic field and the heterogeneous NiC distribution, the pyramidal architecture enables

more effective utilization of the intrinsic dielectric loss capability of the composite matrix [41].

3.8 Scalability and manufacturing outlook

The theoretical scalability of the proposed design framework to other frequency bands (e.g., S, Ku, or Ka bands) is primarily governed by geometric scaling laws and the sub-wavelength condition. Proportional resizing of the pyramids can adapt the impedance matching performance to different wavelengths; however, practical implementation is bounded by FDM resolution limits. For instance, scaling down for higher frequencies (Ka-band) may challenge the 0.8-mm nozzle's ability to maintain tip sharpness, which is critical for minimizing surface reflection. It should be noted that the present NiC-based composite system was experimentally optimized for dielectric-dominant attenuation within the X-band (8.2–12.5 GHz); extension to substantially different frequency ranges would require coordinated re-optimization of both geometric dimensions and filler configuration.

From a large-scale manufacturing perspective, the transition to conformal or curved surfaces (e.g., UAV wings) is facilitated by the rheological stability of the 60 wt% NiC composite. Its high zero-shear viscosity (η_0) prevents structural sagging, ensuring geometric fidelity during complex path planning. Furthermore, the 30% infill strategy offers a dual advantage: it provides a ~58% weight reduction and significantly decreases production time, making it suitable for rapid manufacturing in swarm drone applications. To promote consistent electromagnetic performance across large areas, standardized parameters—such as disabling the retraction feature for high-viscosity flow control—and potential in-situ process monitoring are essential to mitigate microstructural defects and maintain functional uniformity.

4 Conclusion

This study presents a comprehensive multi-stage design framework for the development of lightweight and printable radar-absorbing materials (RAMs), integrating material, process, and geometry optimizations in a sequential manner. Initially, conventional compression molding (CM) was employed to identify the optimal NiC filler content by systematically evaluating

the electromagnetic performance across varying compositions and thicknesses within the X-band. The 60 wt% NiC formulation yielded the best performance under CM at approximately 2 mm thickness, exhibiting deep dual-band absorption, though it did not fully span the entire X-band. Complementary rheological and thermomechanical characterizations provided critical insights into the material behavior that informed processability. Steady-shear flow tests fitted to the Cross model revealed a significant increase in zero-shear viscosity (η_0) at 60 wt% NiC consistent with the formation of a percolated microstructure. Importantly, the Cross model parameters were not used solely for descriptive rheology, but as predictive indicators of FDM manufacturability, directly guiding filament extrusion stability and dimensional fidelity during printing. The flow behavior index (n) decreased with filler loading, facilitating shear-thinning flow and directional orientation during printing. In contrast, the consistency index (k) exhibited only marginal variation, indicating that the shear resistance at moderate rates remained relatively stable across compositions. DMA results showed a notable increase in storage modulus (E') with NiC addition, indicating structural reinforcement. However, the relaxation observed near the glass transition temperature was attributed to weak interfacial interactions between the NiC particles and the matrix, which may narrow the effective service temperature range by promoting localized softening. Furthermore, the modified Guth model revealed a decline in dispersion quality at higher filler loadings, in agreement with the rheological evidence of microstructural densification.

These combined findings guided the optimization of the FDM process to replicate the CM-level performance. Among the tested infill patterns, the concentric geometry demonstrated the best dielectric response and RL profile, closely matching the CM benchmarks. Electromagnetic measurements indicated that the absorption mechanism was governed primarily by lossy dielectric behavior, driven by interfacial polarization (Maxwell–Wagner–Sillars effect) and conductive network losses, while magnetic loss contributions remained limited. Architectural optimizations using three pyramidal structures (FS-10, FS-20, FS-30) demonstrated that FS-10 favored the lower X-band, FS-30 favored the upper X-band, and FS-20 provided the broadest and most balanced absorption bandwidth within the X-band highlighting the critical role of the height-to-period ratio in

impedance matching and broadband performance. Infill ratio adjustments further enabled mass optimization without compromising performance: 30% infill reduced the sample weight by ~ 58% preserving and, in certain frequency ranges, locally enhancing *RL* bandwidth and dip depth compared with fully solid counterparts. The most favorable performance-to-weight balance within the investigated configurations was achieved at 30% infill, whereas the shell-only (0% infill) structure, despite ~ 73% mass reduction, maintained strong mid-to-upper-band absorption but showed reduced low-band performance and did not surpass the 30%-infill FS-20 case in broadband balance.

Collectively, this work shifts RAM design from density-driven optimization toward a validated material–process–geometry co-optimization strategy. The study demonstrates that broadband attenuation can be achieved not solely through filler loading, but through FDM-enabled geometric design strategies that enhance wave penetration and internal attenuation. This integrated methodology defines a transferable and scalable framework for frequency-specific, lightweight RAM systems beyond conventional flat or fully dense designs.

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Author contributions

****Zuhal Yurtbasi****: Conceptualization; Methodology; Investigation; Software; Data curation; Formal analysis; Visualization; Writing—original draft. ****Zeynep Keskin****: Formal analysis; Validation; Data curation. ****Alper Kasgoz****: Conceptualization; Methodology; Resources; Supervision; Project administration; Visualization; Writing—review & editing; Funding acquisition.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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