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Design and Development of a Flexible AMC-Backed Meander Line Antenna for Wearable ISM Band Biomedical Applications- A Review

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Abstract- Wearable biomedical devices require compact, mechanically compliant antennas that maintain reliable wireless links in the presence of lossy, high-permittivity human tissue. At the 2.4-GHz Industrial, Scientific and Medical (ISM) band, conventional planar antennas can suffer impedance detuning, reduced radiation efficiency, pattern distortion, and elevated power absorption when placed close to the body. This review examines the combination of a meander-line radiator and an artificial magnetic conductor (AMC) as a practical route toward a flexible, low-profile antenna platform for wearable health-monitoring systems. Meander loading increases the effective current path within a limited footprint, while an appropriately designed AMC provides an in-phase reflection response near the operating band and can suppress backward radiation toward the wearer. The review summarizes flexible substrate and conductor options, AMC unit-cell design, antenna–AMC spacing, body-equivalent testing, bending effects, and specific absorption rate (SAR) assessment. Published examples demonstrate that AMC integration can improve realized gain and reduce tissue exposure, although reported values depend strongly on geometry, phantom properties, input power, and measurement conditions. A development workflow and a set of recommended validation metrics are proposed. The paper is a literature-based review and design framework; it does not claim original simulated or measured performance for a newly fabricated antenna.

Keywords—Artificial magnetic conductor; meander-line antenna; wearable antenna; ISM band; biomedical telemetry; flexible substrate; specific absorption rate.

I. INTRODUCTION

Wearable biomedical electronics are increasingly used for continuous monitoring of physiological parameters such as temperature, heart rate, respiration, motion, and activity. Sensors mounted on clothing or directly attached to the body must transfer measurements to a nearby gateway, smartphone, or clinical monitoring unit. Wireless Body Area Network (WBAN) links commonly employ compact antennas, and the 2.4-GHz ISM allocation (2.400–2.4835 GHz in many regions) is attractive because it supports widely available low-power radios and protocols. The antenna is a critical part of this link: it must remain matched and efficient while its environment changes with posture, clothing, sweat, and proximity to tissue.

Human tissue has a relatively high dielectric constant and conductivity compared with air and many textile substrates. Near-field coupling to the body changes the antenna's effective electrical length and input impedance; tissue absorption can also reduce outward radiation. A flexible meander-line radiator can reduce footprint, while an AMC reflector can improve front-to-back radiation and provide electromagnetic isolation. Their combined use is therefore a compelling design direction for a wearable biomedical antenna [1]–[4].

1. Scope And Review Method

This article synthesizes peer-reviewed and conference literature on flexible meander antennas, textile and polymer wearable antennas, and AMC-backed structures relevant to the 2.4-GHz ISM band. It emphasizes design mechanisms and comparable metrics rather than attempting a statistical meta-analysis. Published results are quoted with their original context; differences in substrate, AMC size, body model,

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and SAR averaging prevent direct one-to-one comparison.

2. Meander-Line Radiator For Flexible Wearable Systems

A meander-line antenna folds a conductive path into alternating horizontal and vertical sections. The folded geometry increases the current path length without requiring a proportionally larger physical footprint. In first-order terms, resonance is governed by the total electrical length, the effective permittivity of the surrounding medium, and the end effects of the conductor. The meander pattern can therefore support miniaturization, but tight spacing between adjacent segments increases distributed capacitance and may introduce additional loss or narrow the impedance bandwidth.

For a 2.45-GHz design, the free-space wavelength is approximately 122 mm. A quarter-wavelength reference is about 30.6 mm, although the actual resonant path can be shorter or longer depending on dielectric loading, fringing fields, feed topology, and the coupling to the AMC. The radiator may be implemented using copper foil, flexible printed copper, conductive fabric, embroidered conductive yarn, or printed conductive ink. Copper offers predictable conductivity and straightforward fabrication; textile conductors offer comfort and conformability but can exhibit higher sheet resistance, seams, and deformation-dependent contact resistance.

Ali et al. reported a flexible meander-line monopole intended for on- and off-body healthcare links, demonstrating the feasibility of a wearable meander structure and evaluating performance on the chest and arm [1]. Their later conference work further explored a flexible meander-line monopole for WMBAN applications [2]. These studies underline the need to evaluate the antenna both in free space and on representative body locations, since free-space matching alone is insufficient for a biomedical wearable.

3. Key Geometrical Parameters

Important design variables include total meander length, strip width, inter-segment gap, number of turns, ground-plane dimensions, feed transition, and the distance from the radiator to the AMC. Increasing the number of turns can lower resonance or shrink the footprint, but excessive folding increases conductor loss and mutual coupling. Wider strips generally reduce ohmic loss and can broaden bandwidth, although they occupy more area and alter the input impedance. The final geometry should be optimized with a full-wave solver using the actual flexible material properties.

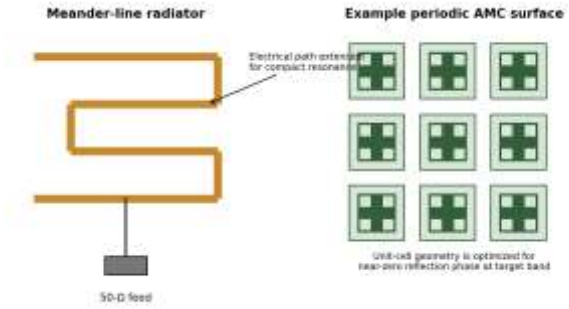


Fig. 1. Conceptual plan view of a meander-line radiator and a periodic AMC surface

4. Feed And Impedance Matching

A 50-Ω microstrip or coplanar-waveguide (CPW) feed can be selected according to the fabrication process and ground arrangement. A CPW feed is convenient for single-layer patterning and integration with a compact ground, whereas a microstrip feed can provide a defined backside ground. Matching should be checked after AMC integration because the reflector changes the radiator's near-field boundary conditions and input impedance. A practical target is |S11| below −10 dB across the required channel bandwidth, with adequate margin for bending and body loading.

5. Artificial Magnetic Conductor: Operating Principle And Design

An artificial magnetic conductor is a patterned, usually periodic, resonant surface designed to exhibit a high surface impedance over a selected frequency range. Unlike a conventional perfect electric conductor, whose reflected electric field has approximately 180° phase reversal at the surface, an AMC can provide a reflection phase near 0° around its resonance. This in-phase reflection enables a low-profile radiator to be positioned relatively close to the reflector without the severe cancellation that can occur above a conventional metal ground plane.

A typical AMC unit cell contains a conductive patch or resonant motif separated from a ground plane by a dielectric layer. Its resonance is governed by the effective inductance and capacitance of the geometry and substrate. The reflection-phase response is often evaluated using periodic boundary conditions and a normally incident plane wave. The useful AMC bandwidth is commonly defined by a reflection phase between +90° and −90°, although the exact design criterion should be stated. For wearable use, the AMC must be flexible, sufficiently thin, and mechanically stable while maintaining the required phase response under curvature.

A finite AMC array placed behind the meander radiator acts as a reflector and partial electromagnetic shield. It can redirect more radiated power away from the body, improve realized gain in the outward direction, and reduce back radiation. The degree of improvement depends on array size, unit-cell geometry, radiator-to-AMC separation, operating bandwidth, and the body's loading. A compact AMC may be designed with square, circular, ring, Jerusalem-cross, or fractal motifs. Miniaturization techniques such as slots and meandered traces can lower the unit-cell resonance, but may increase ohmic loss or sensitivity to fabrication tolerances.

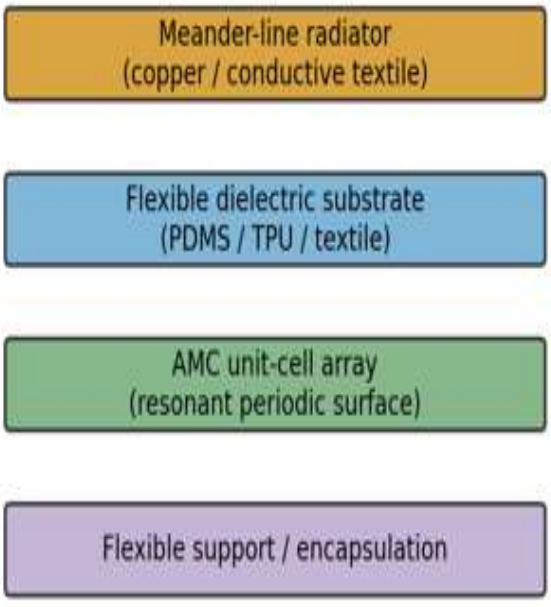


Fig. 2. Conceptual layer stack of a flexible AMC-backed wearable antenna.

6. Integration Considerations

The AMC should be designed for the same target band as the antenna, but its resonant frequency should not simply be assumed to equal the antenna's free-space resonance. The combined structure must be co-optimized. The air or foam gap between radiator and AMC is particularly important: too small a spacing can perturb the current distribution and matching, while too large a spacing increases thickness and may weaken the desired compact reflector behavior. A finite array also has edge effects that are not captured by an infinite periodic-cell model.

7. Flexible Amc Materials

Flexible AMC implementations can use copper or conductive textile patterns on felt, polyester, cotton, polyimide, TPU, or other polymer films. Substrate selection should consider relative permittivity, loss tangent, thickness, bending radius, moisture absorption, skin compatibility, and laundering requirements. Textile thickness and compression can vary between samples; therefore, material characterization should be performed at microwave frequencies rather than relying only on nominal catalogue values.

II. REVIEW OF RELATED WEARABLE ANTENNA STUDIES

The literature indicates that combining conformal radiators with AMC reflectors can improve the outward radiation characteristics of wearable antennas. Gao et al. presented a dual-band conformal antenna based on a meandered monopole and a 3 × 3 annular AMC array, reporting gain enhancement and low 1-g SAR at the 2.45- and 5.8-GHz bands [3]. Youssef et al. described a fully fabric I-shaped antenna with a textile AMC reflector for 2.45-GHz wearable use, reporting a substantial reduction in calculated SAR after adding the AMC [4].

A textile folded-dipole design for on/off-body medical communication was reported with and without a textile AMC array [5]. Its reported results illustrate that the reflector can improve the forward radiation and reduce power absorbed by tissue. A cotton-fabric monopole with a cotton-based AMC was also investigated for 2.45-GHz wearable communication [6]. More recently, a dual-band flexible antenna with AMC backing was reported for 2.45-GHz ISM and 5.8-GHz WLAN

operation [7]. These examples support the use of AMC structures across different flexible material platforms.

A 2025 IEEE Access paper specifically examined a compact AMC-backed meander-line antenna for wearable ISM-band applications and reported high gain, improved front-to-back ratio, and low SAR [8]. This is particularly relevant to the present title because it combines the two principal elements considered in this review. A broader review by Jang et al. and co-authors (see reference [9]) surveys materials, design strategies, and implementation issues for wearable biomedical antennas and circuits. A 2026 study of a miniaturized meander-line antenna for biomedical telemetry at 2.40–2.48 GHz further highlights the continuing interest in meander-based compact radiators [10].

1. Comparative Summary

Table 1. Selected literature examples. Reported values should be consulted in the original papers before direct quantitative comparison.

Study	Antenna / platform	Band / focus	Key reported point
Ali et al. [1]	Flexible meander monopole	Healthcare; on/off body	Measured wearable meander concept; chest/arm tests
Gao et al. [3]	Meander monopole + 3×3 AMC	2.45 / 5.8 GHz	Reported gain increase and low 1-g SAR
Youssef et al. [4]	Fabric I-shaped + textile AMC	2.45 GHz	AMC improved gain and reduced SAR
Textile FDA [5]	Folded dipole + textile AMC	2.4–2.45 GHz	AMC-backed on-body medical link
Saad et al. [6]	Cotton monopole + cotton AMC	2.45 GHz	Textile-compatible AMC approach
Ashyap et al. [8]	Meander line + compact AMC	2.4-GHz ISM	Directly relevant integrated design

2. Proposed Development Framework For The Target Antenna

Based on the reviewed approaches, a practical development route is a compact meander-line monopole or printed patch tuned to the 2.45-GHz ISM band and backed by a flexible AMC array. The proposed framework is intended as a design starting point, not as a claim of a completed antenna. A low-loss flexible dielectric can support the radiator, while a second flexible layer carries the AMC pattern and ground plane. The complete assembly can be encapsulated with a thin, skin-compatible protective layer, provided that encapsulation effects are included in the electromagnetic model.

3. Initial Design Targets

The initial operating target should cover 2.400–2.4835 GHz, with a design margin around the required channel range. The antenna should be optimized for a 50-Ω input, a compact wearable footprint, and a thickness compatible with clothing or a patch enclosure. The AMC should provide a reflection-phase region encompassing the operating band and be large enough to reduce edge leakage. Rather than fixing dimensions before material characterization, the unit cell and radiator dimensions should be selected through parametric optimization.

Table 2. Proposed engineering targets; these are objectives for future design verification, not measured

results.

Parameter	Suggested design objective	Validation method
Operating band	2.400–2.4835 GHz	Measured S11 / impedance bandwidth
Input match	S11 ≤ −10 dB over target band	VNA measurement
AMC reflection phase	Near 0° at band centre; useful ±90° band	Periodic-cell simulation / measurement
Radiation	Outward-directed pattern; reduced back radiation	Anechoic chamber / pattern range
Mechanical flexibility	Stable response at selected bend radii	Flat and curved phantom tests
Exposure	Meet applicable SAR limits for intended jurisdiction	Tissue-equivalent phantom / validated solver
Durability	Stable after flexing, sweat and wash exposure	Repeated-cycle and environmental tests

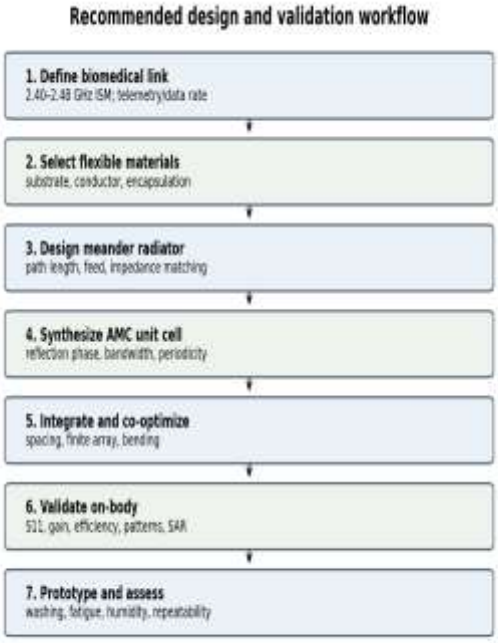


Fig. 3. Recommended design and validation workflow for the proposed flexible antenna.

III. SIMULATION AND OPTIMIZATION

The antenna and AMC should first be modeled separately, then integrated and optimized in a full-wave electromagnetic solver such as Ansys HFSS or CST Microwave Studio. The simulation should include conductor thickness and loss, measured substrate properties, adhesive or spacer layers, and the protective cover. Key sweeps include meander length, strip width, inter-turn gap, AMC cell dimensions,
number of cells, and radiator-to-AMC separation. A multi-objective optimization can minimize |S11| while maximizing realized gain and efficiency and constraining the antenna footprint and SAR.

1. On-Body Performance, Bending And Sar Assessment

A wearable antenna should be evaluated in free space and in close proximity to a realistic body model. A multilayer phantom may include skin, fat, and muscle, with frequency-dependent dielectric properties taken from a recognized tissue-property database. The antenna should be tested at representative locations such as the chest, upper arm, wrist, or shoulder. The separation from the skin must be controlled and reported because even a few millimetres of textile or foam can change the coupling and matching.

2. Bending And Deformation

Bending along the E-plane and H-plane changes the current path, inter-segment coupling, and effective distance between the radiator and AMC. The study should include convex and concave bending, with radii selected to represent the intended body location. For each radius, record resonance shift, −10-dB bandwidth, realized gain, radiation efficiency, and pattern stability.

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A robust design should retain the required communication band under realistic curvature rather than merely returning to its original response after flattening.

3. Specific Absorption Rate

SAR quantifies the rate at which RF energy is absorbed per unit mass of tissue and is expressed in W/kg. It is evaluated using the local electric field and tissue conductivity, with spatial averaging over a prescribed mass (commonly 1 g or 10 g depending on the regulatory framework). The applicable limit depends on jurisdiction, device category, frequency, and test procedure. The manuscript should therefore state the governing standard and averaging mass explicitly; a 1-g result must not be compared directly with a 10-g limit.

The AMC is expected to reduce backward radiation and may lower tissue exposure, but it does not automatically guarantee compliance. SAR depends on input power, antenna placement, phantom properties, mesh convergence, boundary conditions, and the exact averaging algorithm. Simulations should use a conservative input power representative of the intended transmitter and should be validated, where feasible, using a calibrated SAR measurement system. The final product also requires assessment under its actual operating duty cycle and enclosure.

4. Measurement Plan

A complete prototype evaluation should include: (i) S11 using a calibrated vector network analyzer; (ii) realized gain, efficiency, and radiation patterns in an anechoic chamber; (iii) on-body detuning and read-range or link-quality tests; (iv) SAR evaluation using validated numerical and/or measurement procedures; and (v) mechanical durability tests. The test report should document cable routing, connector strain relief, phantom composition, antenna-to-body spacing, bending radius, and uncertainty. A wearable antenna can exhibit cable-induced common-mode current, so a suitable balun or RF choke and repeatable cable arrangement may be necessary.

5. Biomedical Application Potential And Design Challenges

An AMC-backed meander antenna can support low-power sensor nodes for wearable temperature, pulse, respiration, activity, and rehabilitation monitoring. It may also be integrated into smart garments or adhesive patches that relay data to a local hub. In these applications, communication reliability, comfort, washability, biocompatibility, and battery lifetime are as important as peak gain. The antenna should not obstruct the sensing element or create uncomfortable pressure points.

The main challenges are maintaining stable electrical properties under moisture and sweat, preventing conductor cracking during repeated flexing, achieving repeatable textile fabrication, and keeping the AMC sufficiently compact without sacrificing bandwidth. Future work can investigate embroidered or printed conductors, stretchable encapsulation, low-profile AMC unit cells, and joint antenna–sensor co-design. In addition, coexistence with Bluetooth Low Energy, Wi-Fi, and other 2.4-GHz devices should be assessed in realistic indoor environments.

IV. RESEARCH GAPS AND FUTURE DIRECTIONS

Several research opportunities remain. First, many reported prototypes are evaluated under a limited set of bending and body-loading conditions. A systematic protocol covering multiple body locations, bend radii, moisture levels, and garment fits would improve reproducibility. Second, textile substrates are often treated as uniform dielectrics even though weave, compression, humidity, and manufacturing variation can change their microwave properties. Batch-level characterization and uncertainty-aware simulation are therefore recommended.

Third, AMC designs often trade size against bandwidth and fabrication simplicity. Miniaturized resonant cells can become sensitive to tolerances and conductor loss, particularly when fabricated with conductive inks or textiles. Multi-resonant or gradient AMC surfaces may offer wider operating tolerance, but their added complexity should be justified by measured improvements. Fourth, low SAR should be considered alongside outward link performance, since excessive shielding can reduce communication efficiency in some orientations. Finally, long-term wear studies should consider sweat, laundering, skin contact, connector fatigue, and the effect of protective encapsulation.

The incorporation of nanocomposite materials into flexible antenna structures offers a promising approach to enhancing radiation performance while maintaining

compactness, flexibility, and suitability for wearable biomedical applications. Nanocomposites consisting of conductive polymers, carbon-based nanomaterials, silver nanowires, and magnetic nanoparticles can improve electrical conductivity, modify effective permittivity and permeability, and facilitate better electromagnetic energy distribution across the radiating structure. In particular, selectively loading nanocomposite materials into high-electric-field and high-magnetic-field regions of an antenna can improve impedance matching, surface-current distribution, radiation efficiency, gain, and impedance bandwidth. Magnetodielectric nanocomposites are especially attractive because their combined dielectric and magnetic properties provide additional flexibility in antenna miniaturization and resonance optimization. These characteristics make nanocomposite-integrated flexible antennas suitable for the 2.4-GHz ISM band, which is widely employed in wearable health-monitoring devices, wireless body area networks, and biomedical telemetry systems. Therefore, nanocomposite-based antenna engineering provides an effective material-oriented strategy for developing next-generation flexible antennas with enhanced radiation characteristics and reliable wireless communication performance [11]–[14].

V. CONCLUSION

This review has examined the design rationale for a flexible AMC-backed meander-line antenna intended for wearable biomedical communication in the 2.4-GHz ISM band. The meander radiator offers a compact electrical path, while the AMC can provide an in-phase reflecting surface that improves outward radiation and reduces coupling toward the body. Prior studies on flexible meander antennas, textile AMC reflectors, and AMC-backed wearable radiators establish the feasibility of this combined approach. However, performance is highly dependent on substrate properties, unit-cell geometry, finite-array size, radiator spacing, body loading, and deformation. A credible development process must therefore combine full-wave optimization with on-body measurements, bending tests, and SAR evaluation under the relevant regulatory procedure. The proposed framework provides a structured route toward a comfortable, robust, and low-exposure antenna platform for wearable biomedical telemetry.

REFERENCES

1. S. M. Ali, C. Sovuthy, S. Noghanian, Z. Ali, Q. H. Abbasi, M. A. Imran, T. Saeidi, and S. Socheatra, "Design and Evaluation of a Flexible Dual-Band Meander Line Monopole Antenna for On- and Off-Body Healthcare Applications," Micromachines, vol. 12, no. 5, Art. no. 475, 2021, doi: 10.3390/mi12050475.
2. S. M. Ali et al., "Design of Flexible Meander Line Antenna for Healthcare in Wireless Body Area Network Systems," Proc. IEEE EMBC, 2022, pp. 3455–3458, doi: 10.1109/EMBC48229.2022.9871745.
3. H. Gao et al., "A Dual-Band Wearable Conformal Antenna Based on Artificial Magnetic Conductor," International Journal of Antennas and Propagation, 2022, doi: 10.1155/2022/9970477.
4. A. Youssef et al., "A compact fully fabric I-shaped antenna supported with textile-based AMC for low SAR 2.45 GHz wearable applications," Microwave and Optical Technology Letters, 2023, doi: 10.1002/mop.33647.
5. "All-textile inspired-folded dipole antennas for on/off-body communications medical applications," Alexandria Engineering Journal, vol. 61, no. 11, pp. 8751–8761, 2022, doi: 10.1016/j.aej.2022.02.026.
6. A. A. R. Saad, W. M. Hassan, and A. A. Ibrahim, "A monopole antenna with cotton fabric material for wearable applications," Scientific Reports, vol. 13, Art. no. 7315, 2023, doi: 10.1038/s41598-023-34394-3.
7. "Dual-band flexible antenna with AMC backing for wearable applications," Proc. 2024 IEEE MTT-S International Wireless Symposium (IWS), 2024, doi: 10.1109/IWS61525.2024.10713691.
8. A. Ashyap, R. Raad, F. E. M. Tubbal, W. A. Khan, and co-authors, "A Compact AMC-Backed Meander Line Antenna With Low SAR and High Gain for Wearable ISM Band Applications," IEEE Access, vol. 13, pp. 151624–151640, 2025, doi: 10.1109/ACCESS.2025.3603226.
9. "Materials, Designs, and Implementations of Wearable Antennas and Circuits for Biomedical Applications: A Review," Micromachines, vol. 15, no. 1, Art. no. 26, 2024, doi: 10.3390/mi15010026.

10. W. Ali, N. Nizam-Uddin, U. Ullah, M. Zahid, and S. Shoaib, "Electromagnetic Performance Characterization and Circuit-Level Modeling of a Miniaturized Meander-Line Antenna for Implantable and Wearable RFID Applications," Sensors, vol. 26, no. 6, Art. no. 1744, 2026, doi: 10.3390/s26061744.
11. Vasu, Abhilash S., Lakshmi N. R, Aswathi B, and Dana S. "Hybrid Nanocomposite Graphene-TiO_2 and Graphene-ZnO Coated Stub Enhance the Electromagnetic Radiation of Flexible Radiator." Brazilian Journal of Physics 56, no. 2 (2026): 62.
12. Vasu, A. S., N. R. Lakshmi, and T. K. Sreeja. "Nanocomposite-filled slot enhancing radiation of a triple band antenna." Russian Physics Journal 68, no. 11 (2025): 2032-2040.
13. A. S. Vasu, T. K. Sreeja, and N. R. Lakshmi, "Nanocomposite filled slots that enhance radiation of flexible nonagon antenna," Microelectronic Engineering, vol. 294, Art. no. 112258, 2024. https://doi.org/10.1016/j.mee.2024.112258
14. A. S. Vasu et al., "Magnetodielectric nanocomposite antenna for triple band including 5G," Wireless Personal Communications, vol. 129, 2023. https://doi.org/10.1007/s11277-023-10181-1