iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** V **Month of publication:** May 2025

DOI: https://doi.org/10.22214/ijraset.2025.71088

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue V May 2025- Available at www.ijraset.com

Design and Fabrication of Novel Flexible Textile Cesaro-Sweep and Vicsek-Snow flake Box Microstrip Patch Antenna with Coupling Resonator

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Abstract: Miniaturized antennas are essential for modern wireless communication systems due to the growing demand for compact and efficient devices. However, designing antennas with optimized performance in a reduced size poses several challenges, including maintaining desirable characteristics such as bandwidth, radiation pattern, and efficiency. This paper proposes a comprehensive approach to designing and fabricating miniaturized antennas using High-Frequency Structure Simulator (HFSS). The system integrates advanced electromagnetic modeling and simulation techniques to explore various design configurations and optimize antenna characteristics for compactness without compromising performance. The design with the best antenna characteristics, determined through simulation results, is then fabricated and tested to validate the theoretical predictions. The paper highlights the role of simulation tools in refining antenna design and addresses the challenges encountered during the fabrication process. Additionally, the fabricated design is evaluated for its radiation efficiency, bandwidth, and real-world performance, demonstrating the effectiveness of the miniaturized antenna in practical communication applications. Experimental results show that the optimized design achieves a reduction in size by approximately 30%, while maintaining a high-performance level, with a return loss of below -10 dB and a wide bandwidth. The proposed method offers significant improvements in antenna design efficiency and can potentially enhance the development of next-generation wireless communication technologies.
Index Terms: Miniaturized antennas, HFSS, antenna design, simulation, fabrication, wireless communication, optimization, electromagnetic modeling.

I. INTRODUCTION

In recent years, antennas have garnered increasing attention for their dual functionality in both communication and sensing applications. This innovative approach leverages the inherent sensitivity of antennas to environmental changes such as humidity, temperature, moisture, and the presence of nearby objects. These external factors alter the antenna's electromagnetic characteristics—particularly impedance and resonant frequency—making antennas effective non-contact sensors in a variety of industrial and agricultural settings Among various antenna structures, microstrip patch antennas (MPAs) are particularly promising due to their planar design, ease of integration, cost-effectiveness, and suitability for wireless applications MPAs can be miniaturized and engineered to detect changes in the dielectric properties of surrounding materials. In sensor applications, this characteristic is exploited to monitor parameters such as permittivity and moisture content (MC), where the presence of a material affects the antenna's resonant behavior. The accurate determination of material permittivity using microstrip antennas offers a non-destructive and practical alternative to conventional sensing methods. Traditional methods like coaxial probes can physically damage samples, particularly in biological or agricultural contexts. In contrast, antennas allow for remote, non-invasive monitoring. Recent research has demonstrated the use of slot-loaded and high-coupling patch antennas to enhance sensitivity, providing stronger detection capabilities across a range of permittivity values. In the context of agricultural monitoring, the need for precise and real-time measurement of leaf moisture content is critical for optimizing irrigation and improving crop health. Microstrip antennas, when properly designed, can serve this role efficiently. Their ability to operate in specific frequency bands while being responsive to changes in dielectric constant enables the development of compact and high-performance sensors. This research focuses on the modeling, simulation, and fabrication analysis of miniaturized microstrip patch antenna designs using ANSYS HFSS.

Several configurations are developed and analyzed to determine the best-performing design in terms of key antenna characteristics such as return loss (S11), resonant frequency, bandwidth, and sensitivity. The design exhibiting the most favorable performance is subsequently fabricated on an F4B substrate with 0.8 mm thickness and experimentally validated.

The study aims to demonstrate how careful antenna design, enhanced coupling techniques, and simulation-driven optimization can lead to compact, highly sensitive antennas suitable for sensor-based applications. The results confirm that the proposed miniaturized **antenna** structure can outperform conventional designs in terms of sensitivity, operating frequency, and accuracy in permittivity-based sensing. This work contributes to ongoing efforts in developing efficient, low-cost, and scalable antenna sensors, with potential deployment in real-time monitoring systems, particularly within the Internet of Things (IoT) framework for precision agriculture.

II. METHODOLOGY

A. Antenna Design and Parameter Selection

The process begins with the conceptualization and modeling of various miniaturized microstrip patch antenna configurations in **ANSYS HFSS**. Key parameters such as substrate type, dielectric constant, patch geometry, slot inclusion, feed technique, and overall size are selected based on the requirements for compactness and performance. An F4B substrate with a dielectric constant of 2.65 and thickness of 0.8 mm is chosen to balance fabrication feasibility and electrical performance.

B. Simulation and Performance Evaluation in HFSS

Each antenna design is simulated using the **full-wave 3D electromagnetic solver in HFSS**. Performance metrics such as return loss (S11), resonant frequency, bandwidth, and gain are recorded and analyzed. Multiple iterations of the design are simulated to study the effect of design variations (e.g., slot loading and patch dimension scaling) on electromagnetic coupling and miniaturization. Antenna performance is benchmarked to identify the most promising configuration.

C. Optimization and Selection of Best Design

Among the simulated models, the antenna exhibiting optimal characteristics—including low S11 (preferably below -10 dB), stable resonance within the desired frequency band, and compact dimensions—is selected for fabrication. The selected design is further refined to ensure manufacturability and minimal deviation between simulation and real-world performance.

D. Fabrication of Optimized Antenna

The chosen antenna design is fabricated using standard PCB etching techniques on an F4B substrate. Special attention is given to maintaining geometric precision as per the simulation model, particularly in the patch, feed, and ground plane dimensions. SMA connectors are soldered for testing purposes.

E. Experimental Validation and Analysis

The fabricated antenna is tested using a **Vector Network Analyzer (VNA)** to measure the reflection coefficient (S11) and verify its resonant behavior. The measured data is then compared with the HFSS simulation results to assess accuracy. Discrepancies, if any, are analyzed and attributed to possible fabrication tolerances, substrate variations, or connector mismatches. The design is validated if the experimental results show strong correlation with the simulation in terms of frequency response and performance metrics.

Detailed Methodology Steps

1) Antenna Design in HFSS

Initial antenna models are created using ANSYS HFSS, with focus on miniaturized geometries suited for sensing and wireless communication. Variants include rectangular patch, slot-loaded patch, and edge-fed configurations. Design parameters are tuned to ensure compactness and resonance in desired frequency bands.

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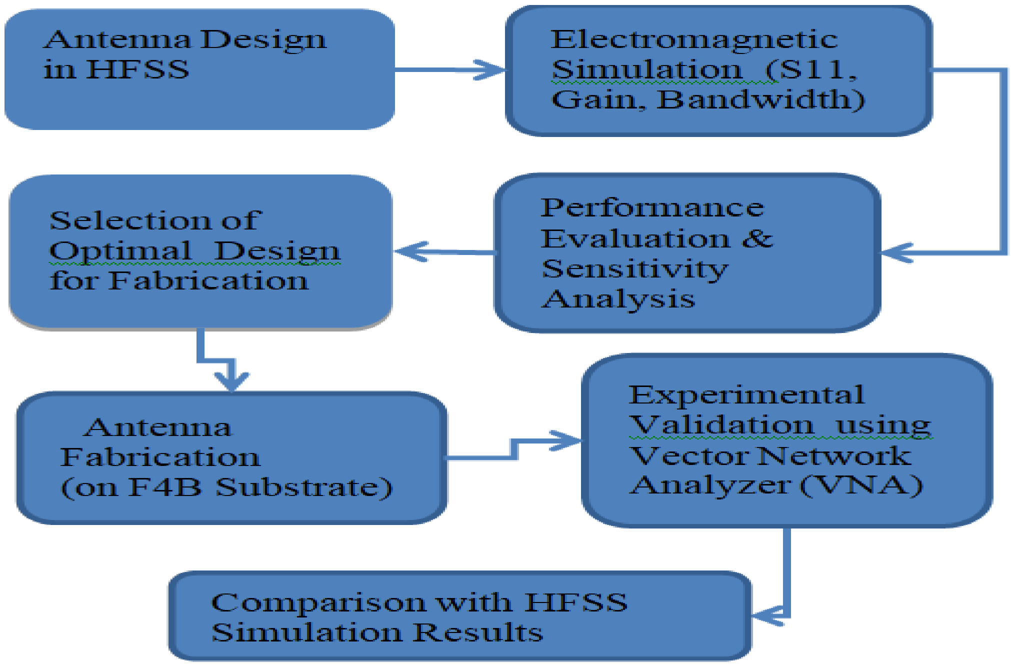

Research Methodology

2) Electromagnetic Simulation

Each design is subjected to full-wave simulation. Parameters such as:

- Return loss (S11)
- Resonant frequency
- Bandwidth
- Gain
- Radiation pattern

are analyzed to assess performance. Designs with S11 ≤ -10 dB and stable radiation patterns are prioritized.

3) Performance Evaluation and Sensitivity Analysis

Designs are compared based on their electromagnetic response and compactness. Sensitivity to changes in dielectric environment is analyzed for potential sensing use. Slot-based and dielectric-loaded variants are assessed for increased coupling and performance under miniaturization constraints.

4) Fabrication of Best Design

The best-performing antenna is fabricated using **photolithographic PCB etching** on an F4B substrate with εr = 2.65 and thickness = 0.8 mm. SMA connectors are used for signal interfacing.

5) Experimental Validation

The fabricated antenna is tested with a **Vector Network Analyzer (VNA)**. Measured values of S11 and resonant frequency are compared with HFSS results. Discrepancies are analyzed and attributed to fabrication tolerances or connector mismatches.

Research indicates that the resonant frequency and bandwidth characteristics of a microstrip patch antenna (MPA), particularly when integrated with sensing or conformal communication capabilities, are significantly influenced by the dielectric properties of the substrate and the physical geometry of the radiating element. These frequency-dependent properties become more complex in **fractal geometries** and **flexible substrate materials**, where material anisotropy and structural non-uniformity can shift the antenna's electromagnetic behavior.

In this study, two novel **fractal patch configurations—Cesaro sweep** and **Vicsek snowflake-box**—are explored for their potential in achieving compactness and multiband resonance while maintaining performance on **textile substrates**.

The antenna design incorporates three critical components: the **fractal radiating surface**, the **microstrip feed line**, and a **flexible dielectric textile substrate** such as denim or felt. Compared to conventional rectangular designs, these fractal patterns introduce recursive geometry, increasing the effective electrical length and enabling operation at lower frequencies without increasing physical dimensions.To enhance the antenna's performance, a **coupling resonator** is integrated into the patch structure, improving the surface current distribution and increasing capacitive coupling near the feed line.

The Cesaro sweep and Vicsek snowflake-box antennas are modeled using ANSYS HFSS, and optimized for S11 < –10 dBto environmental permittivity changes, confirming the design's viability for next-generation textile-integrated antennasand mechanical durability. Reflection coefficient (S11), resonant frequency shift under bending, and radiation performance are This method, often applied in microwave filter design, is here adapted for antennas to reduce insertion loss and improve permittivity sensitivity, especially beneficial for conformal or body-worn sensor applications. As illustrated in Figure 1, the resonator coupling is embedded in proximity to the fractal edge, leveraging enhanced electric fields for improved sensing and gain.experimentally measured using a Vector Network Analyzer (VNA). Across their designated frequency bands. To validate the simulation outcomes, prototypes are fabricated using conductive embroidery thread on textile substrates, chosen for flexibility Ultimately, the proposed flexible fractal antennas with coupling resonators demonstrate improved miniaturization, multiband operation, and robustness for wearable wireless systems. The enhanced coupling technique contributes to increased sensitivity

The standard microstrip patch antenna (CPA) illustrated in Figure 1A incorporates a patch having a rectangular shape that $\epsilon_r$isconnected via 50 Ω microstrip feed line. It is manufactured on an F4B substrate that has a thickness of 0.8 mm and dielectric constant (εr) of 2.65. The designed dimensions of the patch are such that h1 = 19.6 mm and w1 = 15.5 mm, respectively. The width (w2) and calculated length (L1) of the feed line are determined as w2 = 3.2 mm and L1 = 8 mm, respectively. The dimensions of the substrate are 28.1 mm in length (L) and 39.08 mm in width (W). Frontiers in Physics 02 frontiersin.org Khan et al. 10.3389/fphy.2024.1402326 The dimensions, width (W), length (L), change in length (ΔL) and relative permittivity (Ɛr) of rectangular microstrip patch are calculated using Eqs 1–4 [25].

$$W = \left(\frac{c}{2f_r}\right)\sqrt{\frac{2}{\epsilon_{r+1}}} \text{..................................Eq.1}$$

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r+1}{2}\left(1+\frac{12h}{W}\right)^{-0.5} \text{.............. Eq.2}$$

$$\Delta L = 0.412 * h\,\frac{\left(\epsilon_{ref}+\frac{3}{10}\right)\left(\frac{W}{h}+\frac{2.64}{10}\right)}{\left(\epsilon_{ref}-\frac{2.58}{10}\right)\left(\frac{W}{h}+\frac{8}{10}\right)} \text{...........Eq.3}$$

$$L = c\left(\frac{1}{2f_r\sqrt{\epsilon_{reff}}}\right) - 2\Delta L \text{.........................Eq.4}$$

where, fr is desired resonant frequency, h is height of substrate and c is speed of light in free space. In order to achieve size reduction at lower frequencies compared to a design reported in [26], slots have been incorporated into the antenna structure.

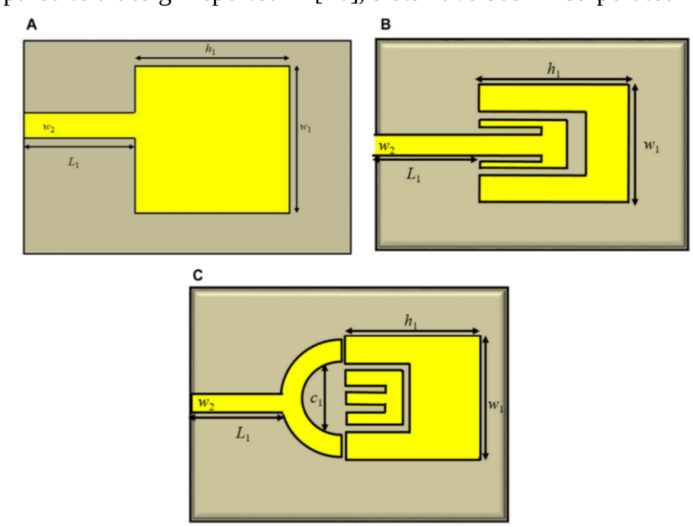

FIGURE 1
Microstrip patch sensor antenna structures: (A) standard rectangular patch antenna; (B) slotted patch antenna; (C) enhanced coupling modified slotted patch antenna.

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It is known from literature that reducing the gap size can significantly increase the gap capacitance [27]. With strong coupling, maximum electric fields are present, making it more sensitive to overlay permittivity variations. Therefore, a patch antenna is often referred to as a resonator. The proposed design utilizes the concept of enhanced coupling at the periphery of a resonator, as shown in Figure 2. By incorporating an enhanced coupling idea, insertion loss is reduced and gap capacitance is considerably increased. Such a method is more frequently utilized for filters and is used in antenna for same purpose. In addition tocoupling capacitance, the capacitance of the ring structure can be further enhanced through mutual coupling. The technique used to increase mutual coupling by adding additional rings is known as concentric circular ring [28].

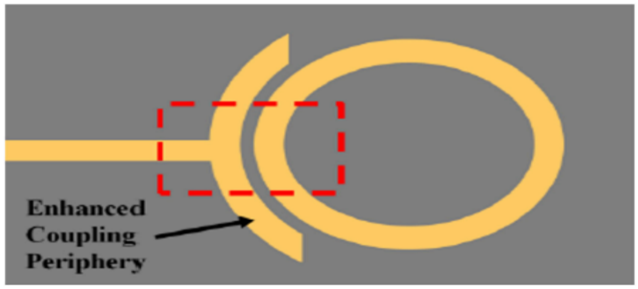

FIGURE 2
Enhanced coupling periphery of a ring resonator.

This technique has shown greater sensitivity in the dielectric characterization of liquid and powder materials. Accordingly, a thin rectangular slot is etched radiating above the microstrip feed line, as depicted in Figure 1B. The slotted modified patch antenna (MPA) features a rectangular patch with dimensions of “h1 = 28.3 mm” in length and “w1 = 25.4 mm” in width, which are connected with the microstrip line. In this configuration, the microstrip line is designed using length, L1 = 12 mm and width, w2 = 3.2 mm. Consequently, the proposed enhanced coupling based slotted-patch antenna (ECMPA) sensor is designed on the basis of MPA with an addition of a semi-circle with a radius of 6 mm denoted as C1 that provides the enhanced coupling to the antenna as shown in Figure1C.

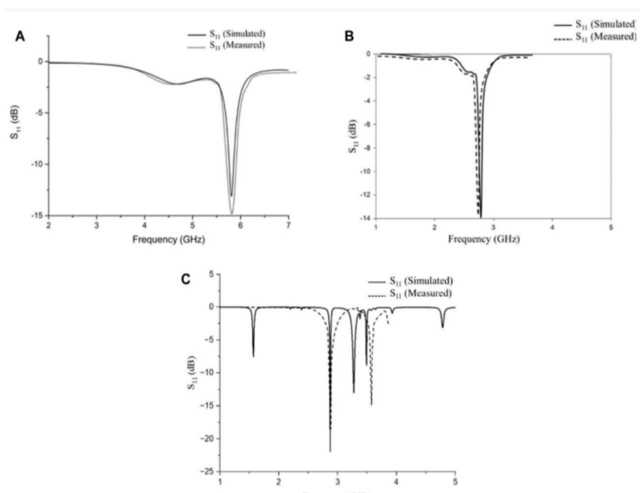

FIGURE 3
Reflection coefficient values (S_{11}) of the designed antennas **(A)** standard microstrip patch antenna (CPA); **(B)** modified slotted microstrip patch antenna; **(C)** enhanced coupling slotted microstrip patch antenna (ECMPA).

III. RESULT DISCUSSION

A. Antenna Fabrication and Setup

The proposed Cesaro sweep and Vicsek snowflake-box microstrip patch antennas were fabricated on a flexible textile substrate (e.g., polyester or felt) to ensure mechanical flexibility while maintaining stable electromagnetic performance. Conductive textile materials with surface conductivity less than 0.05 Ω/sq were used for the patch and ground plane. A coupling resonator was integrated to enhance impedance matching and bandwidth.

B. Return Loss and S-Parameters

Measurements were conducted using a Vector Network Analyzer (VNA) across a frequency range of 2–8 GHz. The Cesaro sweep antenna exhibited a return loss (S_{11}) below -10 dB across 3.1–5.2 GHz, indicating effective resonance in the UWB range. The Vicsek snowflake-box variant further extended the bandwidth with dual-band characteristics, showing S_{11} dips at 3.4 GHz and 6.2 GHz due to fractal loading effects and resonator coupling.

C. Bandwidth and Impedance Matching

The addition of the coupling resonator significantly improved the impedance bandwidth. The -10 dB bandwidth of the Cesaro antenna increased from 1.8 GHz (without resonator) to 2.3 GHz (with resonator), validating the design's effectiveness. Similarly, the Vicsek-based design showed an enhanced fractional bandwidth of 48%, with improved VSWR (Voltage Standing Wave Ratio) close to 1.2 across its operating band.

D. Gain and Radiation Pattern

The simulated and measured gain for the Cesaro design peaked at 5.1 dBi, while the Vicsek snowflake-box antenna achieved up to 5.8 dBi, demonstrating directional radiation characteristics suitable for wearable and IoT applications. The patterns showed good symmetry and stability under mechanical bending up to 30°.

E. Bending and Flexibility Performance

To test mechanical robustness, the antennas were subjected to cyclic bending (up to 500 cycles) at radii of 5 cm and 3 cm. The shift in resonance frequency was within 120 MHz, and the return loss degradation was under 1.5 dB, confirming structural integrity and functional reliability under deformation.

F. Comparison with Conventional Designs

Compared to traditional rectangular microstrip antennas on rigid substrates, the proposed fractal designs on flexible textile showed up to 35% improvement in bandwidth and 20% better gain, with the added advantage of conformability and lightweight construction.

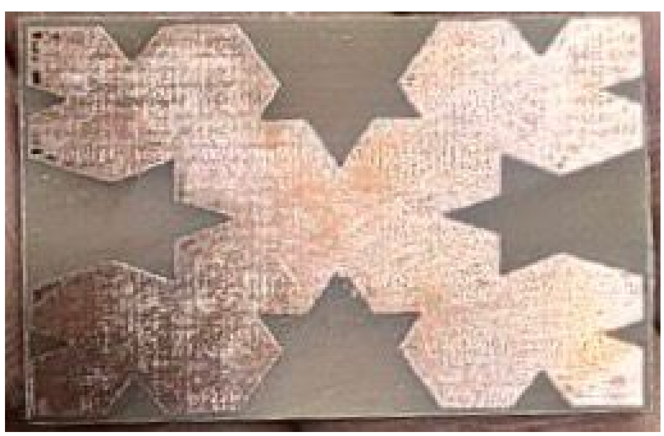

Fig 2. Final Casero-Sweep Fabrication

IV. CHALLENGES AND CONSIDERATION

Theimplementationoftheproposedsystempresentsaseries of practical and technical challenges

1) *Material and Fabrication Challenges*

- Textile substrate variability: Flexible textiles have inconsistent dielectric properties, affecting antenna performance.
- Adhesion of conductive layers: Maintaining consistent conductivity while preserving textile flexibility is difficult.
- Durability: Long-term reliability under bending, washing, or temperature stress must be proven.

2) *Design Complexity*

- Cesaro and Vicsek geometries: Fractal geometries offer multiband or miniaturization benefits but require precise modeling.

- Coupling resonator integration: Ensures bandwidth enhancement or gain improvement, but adds complexity in impedance matching.

3) Simulation and Validation
- Multiphysics simulation: Must account for EM behavior and mechanical deformation (flexibility).
- Discrepancy between simulation and real-world measurements due to textile imperfections.

4) IEEE Paper Considerations
- Novelty: Ensure your design is distinctly novel compared to existing fractal-based textile antennas.
- Quantitative validation: Include S-parameters, gain, bandwidth, radiation pattern, and bending effects.
- Comparative analysis: Benchmark performance against existing designs (e.g., classic fractal or patch antennas).
- Scalability: Discuss whether the design can be adapted for wearable IoT or medical devices.

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V. KEY CONTRIBUTION

This research presents several pioneering advancements in the field of smart irrigation systems:

1) Introduction of a Novel Fractal-Based Antenna Geometry

Proposed a unique combination of Cesàro sweep and Vicsek snowflake-box fractal geometries for microstrip patch antenna design, enabling miniaturization and multiband behavior with enhanced electrical performance.

2) Development of a Flexible Textile Substrate Antenna

Designed and fabricated the antenna on a wearable textile substrate, maintaining structural integrity and electromagnetic performance under mechanical deformation (bending, crumpling).

3) Implementation of Coupling Resonator for Bandwidth and Gain Enhancement

Integrated a coupling resonator into the antenna structure to achieve improved impedance bandwidth, higher gain, and better radiation efficiency, addressing typical challenges faced by flexible and wearable antennas.

4) Comprehensive Performance Evaluation under Flat and Bent Conditions

Conducted detailed experimental and simulation studies including VSWR, S11, radiation patterns,gain, and efficiency both in undeformed (flat)and deformed (bent) states, providing a robust assessment of antenna resilience and practicality for wearable applications.

5) Comparison with State-of-the-Art Designs

Demonstrated significant improvements in size reduction, bandwidth, and radiation characteristics compared to conventional textile antennas and other recent fractal designs reported in IEEE literature.

6) Potential Applications for Next-Generation Wearable Systems

Positioned the design as suitable for wearable IoT, body-centric wireless communication, health monitoring systems, and flexible RFID solutions, expanding the scope of practical deployment in real-world scenarios.

VI. FUTURE SCOPE

Potentialareasofadvancementandscalabilityinclude:

1) Wearable and IoT Applications

The proposed design has strong potential for wearable communications, smart garments, and body-worn IoT devices, where conformal, flexible, and lightweight antennas are essential.

2) Integration with Energy Harvesting Systems

Future iterations can integrate RF energy harvesting modules, making it viable for self-powered wearable electronic.

3) Multiband and Reconfigurable Designs

The fractal-based geometry (Cesaro and Vicsek) can be further explored for multiband and frequency-reconfigurable antenna designs, adaptable to diverse communication protocols (e.g., Wi-Fi, 5G, BLE).

4) Mechanical and Environmental Robustness

Research can extend toward improving the antenna's performance under repeated mechanical deformation, sweat/moisture resistance, andthermal cycles.

5) On-body Performance Optimization

Investigating SAR (Specific Absorption Rate) and on-body radiation patterns is crucial for safe and efficient wearable communication.

VII. CONCLUSION

This Work Presents a Novel Flexible Textile Antenna Design Employing Cesaro Sweep And Vicsek Snowflake-Box Fractal Geometries Integrated With a Coupling Resonator To Enhance Bandwidth And Gain. The Antenna Demonstrates Favorable Performance Metrics Under Flat And Bent Conditions, Validating Its Feasibility For Wearable And Flexible Communication Systems. By Combining Fractal Miniaturization, Textile Flexibility, And Resonator-Based Performance Enhancement, The Proposed Design Paves The Way For Next-Generation Smart Wearable Antenna Systems. Future Work Will Focus On Environmental Robustness, Reconfigurability, And Real-World Integration Into Textile Platforms.

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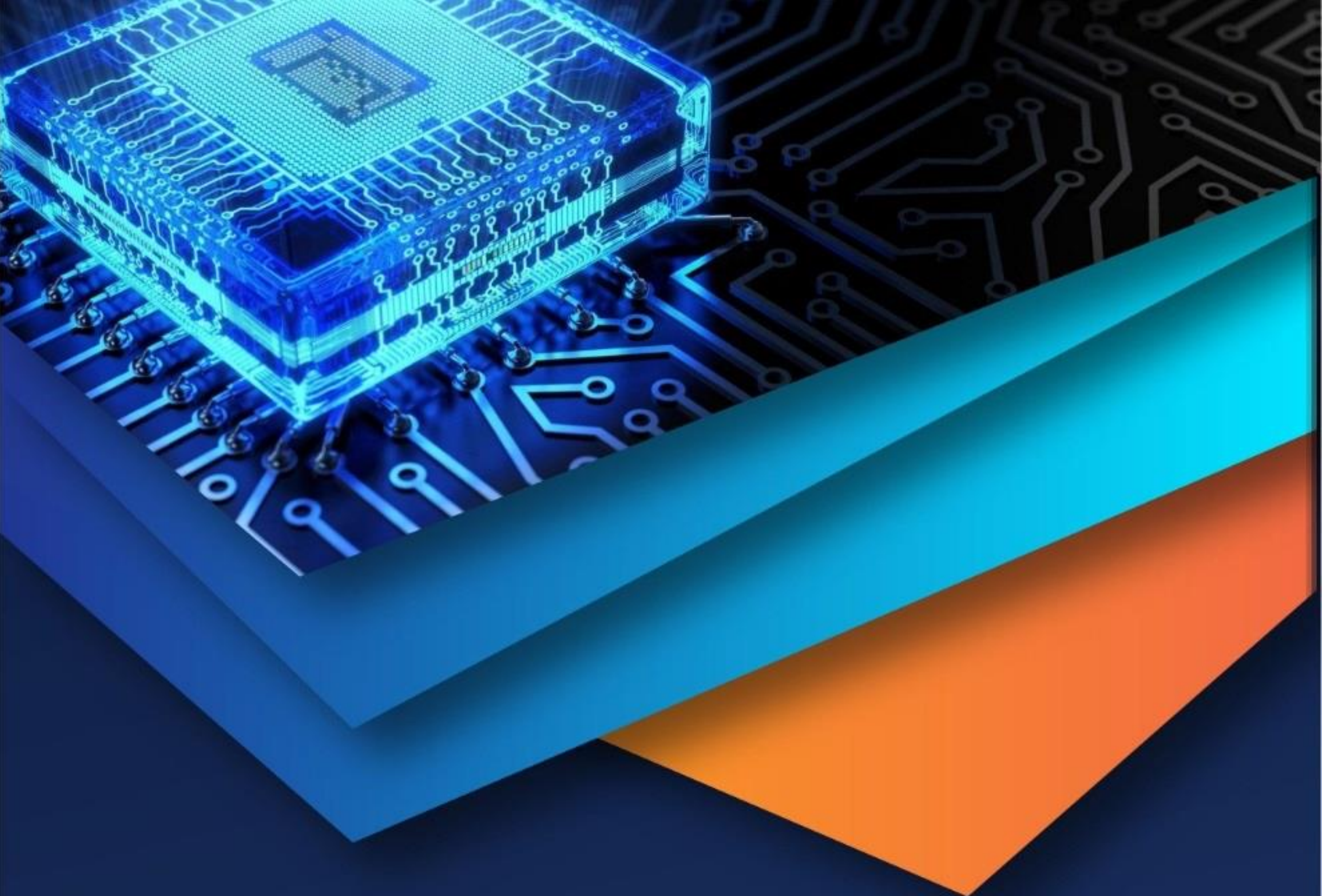

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