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Design and Validation of an Ultra-Wideband Log Spiral Antenna for RF Energy Harvesting

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ABSTRACT

This paper presents the design, simulation, fabrication, and validation of an ultra-wideband (UWB) log spiral antenna engineered for radio frequency (RF) energy harvesting over 500 MHz–3 GHz. The antenna addresses traditional limitations of log-spiral designs, including rapid physical expansion and challenges in achieving low cut-off frequencies. Using CST Studio Suite 2025, the antenna was modelled with optimized geometric parameters derived from analytical equations, enabling compactness while preserving wideband characteristics. Performance evaluations—including return loss (S11), voltage standing wave ratio (VSWR), gain, radiation pattern, and far-field behavior—were conducted. Fabrication was completed using FR4 substrate followed by measurement using a FieldFox vector network analyzer and anechoic chamber. Results demonstrate excellent agreement between simulation and physical measurements, achieving −20.9 dB (simulated) and −32 dB (measured) return loss, and VSWR values near unity (1.06–1.19). The antenna exhibits suitable omnidirectional radiation and efficiencies required for broadband RF energy harvesting. This work confirms the feasibility of developing low-cost, planar, wideband spiral antennas for ambient RF energy capture and provides a practical foundation for integration with rectifying circuits in low-power IoT systems.

Keywords - Log spiral antenna, RF energy harvesting, UWB antenna, CST simulation, FR4 substrate, VSWR, return loss, far-field radiation.

INTRODUCTION AND LITERATURE REVIEW

Energy harvesting from ambient radio frequency (RF) sources has emerged as a viable solution for powering low-power electronic systems, including wireless sensors, mobile devices, and IoT nodes. Traditional battery-dependent systems generate environmental challenges due to chemical waste and finite battery lifecycles. RF energy, in contrast, is pervasive, renewable, and compatible with compact harvesting architectures that combine receiving antennas with rectifying circuits. Antenna selection plays a fundamental role in RF harvesting efficiency, as it determines the ability to capture electromagnetic energy across various frequencies. Log spiral antennas, characterized by their frequency-independent properties, broadband response, and circular geometry, are strong candidates for this application. However, conventional spiral antennas exhibit drawbacks such as excessive size growth with added turns and difficulty achieving low-frequency resonance, limiting their applicability in broad-spectrum environments. Existing literature provides several strategies for improving energy harvesting antenna designs. [1] identified key structural components that influence RF-to-DC conversion efficiency and highlighted miniaturization approaches and harmonic rejection techniques to suppress unwanted reradiation. [2] demonstrated textile-based broadband spiral antennas with flexible substrates, introducing geometric relationships that govern cut-off frequency through inner and outer radii adjustments. [3] extended the analysis of log spirals into terahertz domains using hemispherical lenses, emphasizing the importance of stable input impedance across wide frequency ranges.

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Other researchers explored patch antennas, hexagonal spirals, and log-periodic dipole arrays (LPDAs). [4] compared spiral geometries, revealing the superior packing efficiency and reduced unused substrate area provided by hexagonal spirals. [5] designed a triangular-dipole LPDA with impressive gain stability across 570–2750 MHz, suitable for multiband harvesting. [6] proposed a modified log-periodic spiral integrating split-ring resonators (SRRs) to enhance bandwidth without enlarging antenna dimensions. [[7] investigated RF harvesting circuits, particularly Villard voltage multiplier topologies, and emphasized the necessity of impedance matching between antenna and rectifier. The present work builds upon these advancements by developing a planar log spiral antenna with significantly reduced cut-off frequency (500 MHz) while maintaining compactness suitable for PCB fabrication. Through parameter optimization—specifically inner radius, alpha growth factor, phi increment, and delta offset—the antenna achieves desirable broadband characteristics for practical RF energy harvesting. Experimental results affirm its performance advantages and confirm its suitability for integration into power-autonomous systems.

METHODOLOGY AND DESIGN

The methodological framework for developing the ultra-wideband log spiral antenna involved a sequence of interconnected phases beginning with theoretical modelling, followed by electromagnetic simulation, fabrication using PCB processes, and finally experimental validation. Each phase informed the next, ensuring that the antenna not only fulfilled broadband performance requirements but also maintained structural feasibility for practical RF energy harvesting applications.

$$r = k^{\alpha\varphi} \quad (1)$$

$$r_1 = \frac{C_0}{2\pi f} \quad (2)$$

The design process commenced with the mathematical formulation of the spiral geometry, since the electromagnetic behaviour of a log spiral antenna is intrinsically governed by its exponential radial expansion. The general equation (1) served as the basis for defining the radius as a function of angular rotation, allowing careful control over the antenna's growth rate and bandwidth. Establishing the inner radius r1 was critical, as it determines the highest operating frequency. Using the well-known relationship in (2), the design targeted 3 GHz as the upper frequency limit, resulting in an inner radius of approximately 16 mm. This value subsequently allowed the calculation of the initial radius constant k, which was determined to be 1.31 mm. The parameters α, the growth factor, and φ-increment were chosen based on preliminary studies and literature, with α = 0.5 and φ = 5°, values known to provide adequate spiral unfolding while keeping the antenna compact. The delta angle, set at 90°, controlled the separation between the two spiral arms, Fig. 1 illustrates the final design in CST.

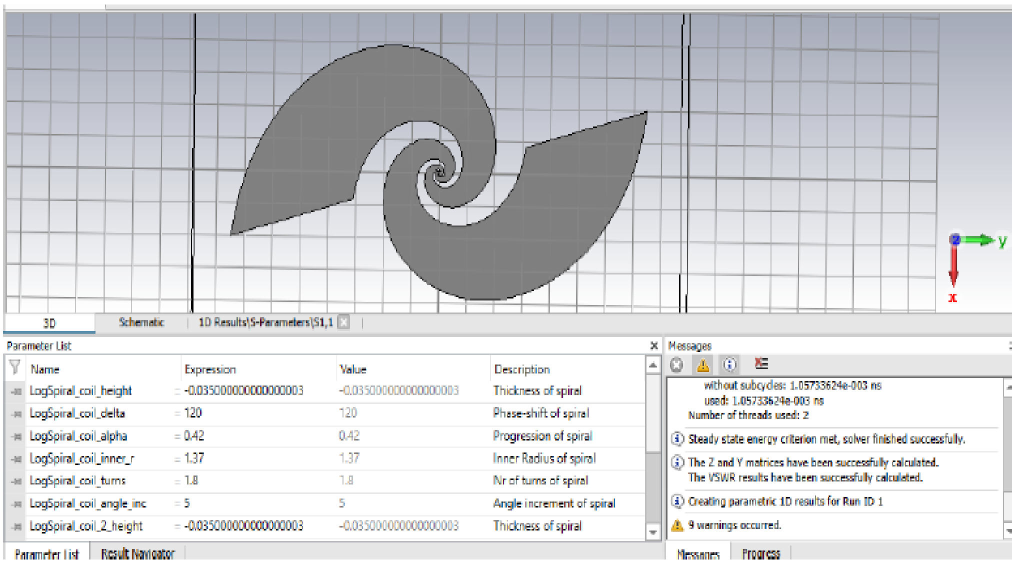

Fig. 1. The final design in CST

Once the theoretical design was established, CST Studio Suite 2025 was employed to simulate and refine the antenna's electromagnetic behaviour. The geometry was constructed using CST's built-in logarithmic spiral macro, after which the second arm was created through rotational duplication of the first. This ensured geometric symmetry, an essential requirement for stable radiation performance. A rectangular FR4 substrate was added beneath the spiral, matching the dimensions expected in the final fabricated prototype. Feeding the antenna accurately in simulation was crucial. Discrete ports were placed at the inner terminals of the spiral arms, boundary conditions were set to "open (add space)", and a broadband frequency sweep from 500 MHz to 3 GHz was defined. The CST time-domain solver was selected due to its efficiency in producing wideband output. Performance parameters—including S11, VSWR, far-field patterns, and current distributions—were examined to validate suitability for RF harvesting. The Log spiral Antenna Parameters used in the simulation I shown in table 1. Following successful simulations, fabrication was conducted using FR4 substrate and standard PCB processes including inkjet printing, UV curing, chemical etching, photoresist stripping, drilling, and soldering. These stages ensured high fidelity between the simulated model and the final prototype. Finally, performance measurements were carried out using a Keysight FieldFox VNA for S11 and VSWR validation, and an anechoic chamber for far-field characterization. These measurements provided real-world confirmation of the antenna's broadband performance.

Table 1. Log Spiral Antenna Parameters

Aspect	Value
Thickness	-0.035
Number of Turns	1.5
Initial Radius, k	1.31
Alpha	0.5
Phi-increment	5
Delta	90

RESULTS AND DISCUSSION

Although the present study focuses on antenna-level performance, the proposed log spiral antenna is well suited for RF energy harvesting systems when integrated with rectifying circuits. The broadband impedance matching and stable radiation characteristics directly influence the available RF power at the rectifier input, which is a key determinant of RF-to-DC conversion efficiency. Previous studies have shown that broadband antennas with low reflection loss enable improved power capture across multiple ambient RF bands when paired with appropriate rectifier topologies. Therefore, the demonstrated performance of the proposed antenna provides a strong foundation for efficient rectenna integration.

The performance of the ultra-wideband log spiral antenna was evaluated through both CST simulations and physical measurements. This dual approach enabled a holistic understanding of the antenna's behavior under controlled electromagnetic conditions and real-world fabrication constraints. The fabricated antenna closely matched its simulated geometry, preserving the exponential spiral shape necessary for stable broadband response. The FR4 substrate provided structural support without introducing excessive dielectric losses. Return loss (S11) results demonstrated strong impedance matching, with simulated values reaching −20.9 dB and measured values achieving −32 dB. This indicates that the antenna effectively captures incident RF energy with minimal reflection. The simulated and measured S11 Reflection Coefficient can be seen in figure 2.

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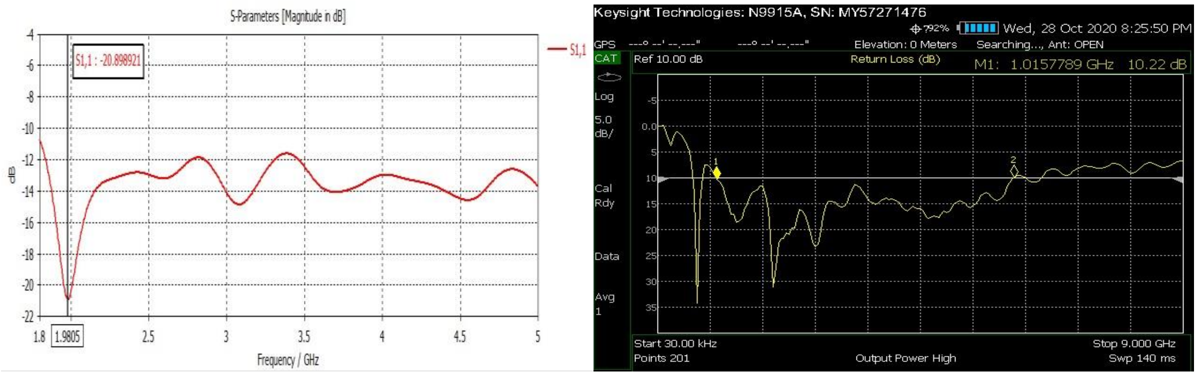

Figure 2. S11 Reflection Coefficient (Simulated and Actual Measurement)

VSWR performance was equally promising, with simulated values of 1.1982 and measured values of 1.0645. These results confirm that the antenna maintains excellent impedance matching throughout the 500 MHz–3 GHz range. The simulated and measured VSWR performance can be seen in figure 3.

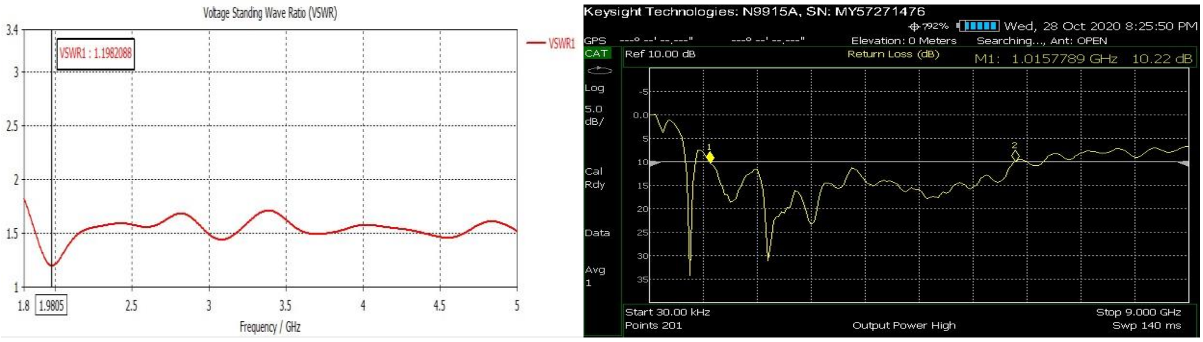

Figure 3. VSWR (Simulated and Actual Measurement)

Far-field radiation measurements showed good agreement between simulation and experiment. The antenna exhibited wide, stable radiation patterns with omnidirectional tendencies in the azimuth plane, making it well-suited for capturing RF energy from multiple directions. The simulated and measured Far field radiation pattern at 2.75 GHz can be seen in figure 4.

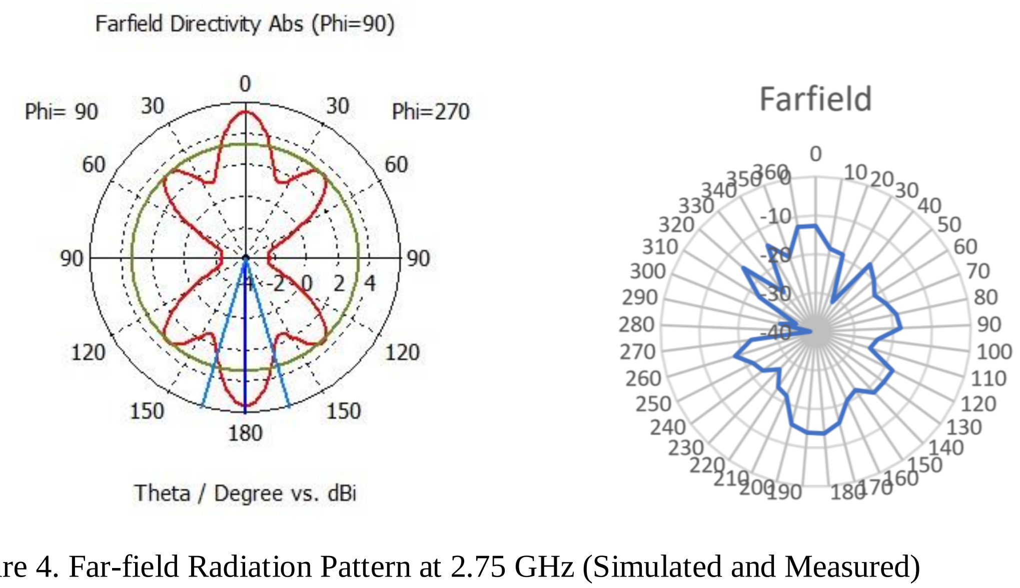

Figure 4. Far-field Radiation Pattern at 2.75 GHz (Simulated and Measured)

In practical deployment scenarios, RF energy harvesting antennas are subject to environmental factors such as multipath propagation, electromagnetic interference, and near-field coupling with surrounding objects. The wide operational bandwidth and quasi-omnidirectional radiation pattern of the proposed log spiral antenna help mitigate these effects by enabling energy capture from multiple incident angles and frequency bands. Such

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characteristics are particularly advantageous in cluttered indoor and urban environments, where RF sources are spatially and spectrally distributed. The comparison summary is presented in Table 2.

Table 2. Comparison with Reported UWB / Log Spiral Antennas for RF Energy Harvesting

Reference	**Antenna Type**	**Frequency Range (GHz)**	**Substrate**	**Size (approx.)**	**Min S11**
[4]	Spiral	0.2–2.4	FR4	Large	−10 dB
[5]	LPDA	0.57–2.75	FR4	Large	−10 dB
[6]	Modified Spiral	0.9–2.4	FR4	Medium	−15 dB
This work	**Log spiral**	**0.5–3.0**	**FR4**	**Compact**	**−32 dB**

Regarding fabrication tolerances, standard PCB manufacturing processes introduce variations in trace width, substrate thickness, and connector soldering. Despite these factors, the close agreement between simulated and measured results indicates that the proposed design is robust against moderate fabrication uncertainties. This robustness is important for scalability and repeatable production of the antenna in practical RF energy harvesting applications.

Overall, the results confirm that the antenna meets the performance expectations of a broadband energy harvesting device, with excellent matching, stable gain characteristics, and consistent radiation behavior. Figure 5 shows the Fabricated Log Spiral Antenna (Front, Rear, Side Views). Figure 6.Shows the anechoic chamber and measurement setup for this project.

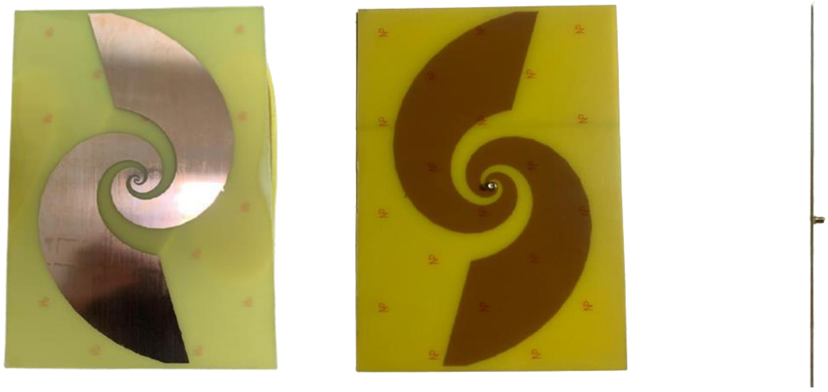

Figure 5. Fabricated Log Spiral Antenna (Front, Rear, Side Views)

Figure 6. Anechoic Chamber and Measurement Setup

CONCLUSION

The development of an ultra-wideband log spiral antenna for RF energy harvesting has demonstrated that a carefully engineered planar geometry can achieve strong broadband performance across a 500 MHz to 3 GHz range. Simulation, fabrication, and measurement were closely aligned, confirming the validity of the proposed design. The antenna's excellent impedance matching, stable radiation patterns, and compatibility with low-cost FR4 substrate make it an attractive candidate for IoT and low-power wireless applications. Its performance provides a strong foundation for integration with rectification and power management circuits to form fully functional RF energy harvesting modules. Future work may extend this study by integrating rectifying circuits and evaluating harvested DC power under realistic environmental conditions, further validating the antenna's suitability for self-powered wireless systems.

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