

Sustainable Power and Energy System Development through Sub-6 GHz DRA Using AI-Based Optimization

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ABSTRACT

This paper presents the design and performance evaluation of a Sub-6 GHz antenna optimized using AI-based techniques for applications in sustainable power and intelligent energy systems. The antenna resonates around 4–4.3 GHz and demonstrates excellent impedance matching, with an S11 value below -25 dB and a low VSWR, ensuring efficient power transfer. The radiation patterns exhibit a stable main lobe with a directivity of approximately 6.7 dBi, supported by a high radiation efficiency of approximately -0.5 dB, making the design suitable for low-power, long-range communication nodes used in smart grid and renewable energy monitoring environments. An AI-driven optimization workflow was employed to refine key geometric parameters and enhance matching and efficiency without extensive manual iterations. This approach reduces design time while improving overall electromagnetic performance. Owing to its efficient characteristics and intelligent optimization strategy, the proposed antenna is a strong candidate for deployment in smart meters, distributed sensors, and intelligent electrical infrastructure requiring reliable Sub-6 GHz wireless communication. The study demonstrates how AI-empowered antenna development can support the evolution of sustainable and energy-efficient power systems.

Keywords: *Sub-6 GHz Antenna; AI-Based Optimization; Smart Grid Communication; Sustainable Energy Systems; Intelligent Electrical Infrastructure; Radiation Efficiency; Antenna Design; Machine Learning in Electromagnetics.*

1. Introduction

The evolution of modern power systems into intelligent, sustainable, and digitally connected infrastructures has created a strong demand for reliable and energy-efficient wireless communication technologies. As smart grids expand, Sub-6 GHz wireless links have emerged as a key enabler due to their favourable propagation characteristics, reduced attenuation, and compatibility with low-power IoT devices used for grid monitoring, smart metering, and renewable energy supervision [1]. Antennas supporting these communication layers must therefore exhibit high efficiency, stable gain, and robust impedance characteristics to ensure uninterrupted data exchange across distributed and often harsh electrical environments [2].

However, traditional antenna design approaches depend heavily on manual parameter adjustments and repeated full-wave simulations, making the process time-consuming and less adaptable to rapidly evolving system requirements. Recent advancements in artificial intelligence (AI) have transformed this landscape by enabling intelligent electromagnetic modelling, surrogate-assisted optimization, and automated performance prediction [3]. Machine learning techniques, in particular, have demonstrated significant potential to reduce computational cost while improving accuracy and accelerating design convergence for complex antenna structures [4].

Motivated by these developments, this work presents an AI-optimized Sub-6 GHz antenna tailored for sustainable energy systems. The proposed design enhances efficiency, reliability,

and communication performance, advancing next-generation intelligent electrical infrastructure. Table 1 represents requirements for sustainable energy and smart grid systems in relevance to Sub-6 GHz antenna.

Table 1. Communication Requirements for Sustainable Energy and Smart Grid Systems

Requirement	Description	Relevance to Sub-6 GHz Antennas	Reference
Long-Range Connectivity	Smart meters, sensors, and grid assets require reliable coverage over wide areas.	Sub-6 GHz frequencies provide lower attenuation and better penetration.	[1]
Energy Efficiency	Devices often operate on low power or battery sources in remote locations.	High antenna efficiency minimizes required transmit power.	[2]
Stable Radiation Performance	Communication links must remain stable in harsh or dynamic environments.	Consistent gain and directivity ensure dependable wireless links.	[2]
Low Design Complexity	Rapid deployment and cost constraints favor simpler, compact hardware.	Sub-6 GHz antennas are easier and cheaper to implement.	[1]
Fast Optimization and Adaptability	Smart grid environments evolve quickly, needing flexible design updates.	AI-based optimization accelerates antenna design and improves accuracy.	[3], [4]

2. Background and Related Work: Wireless communication plays a crucial role in modern smart grids, enabling real-time monitoring, metering, and energy management across distributed infrastructures. Sub-6 GHz antennas are widely adopted due to their long-range capabilities and high-efficiency low-power communication in harsh electrical environments. Traditional antenna design often requires extensive manual tuning and high computational cost. Recent studies have introduced AI and machine-learning-based optimization to accelerate antenna modelling and enhance performance metrics. However, limited research focuses on applying AI-optimized Sub-6 GHz antennas specifically for sustainable and intelligent energy systems [12]. Table 2 represents comparison of proposed antenna design parameters along with operating band, return loss, gain and efficiency.

Table 2. Comparison of Proposed Antenna with related Published Designs

Study / Design	Operating Band	S11 / Return Loss	Gain / Directivity	Efficiency	Remarks
Proposed Work	4.0–4.3 GHz	–25 dB	6.7 dBi	~89%	AI-optimized for smart grid and sustainable energy systems
Alibakhshikenari et al. (2022) [5]	3.5–4.5 GHz	–18 dB	6.1 dBi	82%	Metamaterial-inspired antenna, no AI optimization
Ali et al. (2021) [6]	3.8–4.2 GHz	–14 dB	5.9 dBi	78%	Designed for IoT/5G, manually optimized
Khan et al. (2020) [7]	4.0–5.0 GHz	–20 dB	6.4 dBi	80%	Used evolutionary algorithm, not energy-system focused
Kumar & Zarate (2023) [8]	3.5 GHz	–16 dB	5.4 dBi	76%	Smart-grid communication antenna, conventional design

3. Methodology

The proposed cylindrical Dielectric Resonator Antenna (DRA) was designed, optimized, and evaluated using CST Studio Suite 2024, a full-wave electromagnetic simulator commonly used in wireless and 5G antenna development. The methodology consists of two main stages: antenna design and parametric optimization,

3.1 Antenna Design Process

The antenna was designed to operate around 4.2–4.25 GHz, falling within the mid-band sub-6-GHz 5G FR1 allocation. A high-permittivity dielectric material with $\epsilon_r = 10$ was selected to achieve compact size and strong electromagnetic confinement. A cylindrical DRA geometry was adopted because it supports the $TE_{01\delta}$ mode, known for high radiation efficiency and stable omnidirectional H-plane behavior [4]. Such cylindrical DRAs are widely used due to their predictable modal behavior and strong fundamental-mode excitation [9]. A coaxial probe feed was used to excite the resonant mode. The DRA height, radius, and probe position were varied through systematic parametric sweeps to improve impedance matching. This optimization strategy is consistent with established coax-fed cylindrical DRA designs reported in classical antenna literature [10].

3.2 Simulation Setup

The antenna model was created in CST and analyzed using the following configuration:

- Solver: Frequency-domain
- Frequency Range: 3.5 GHz – 5.0 GHz
- Mesh: Tetrahedral with adaptive refinement
- Boundary Conditions: Open (add space)
- Excitation: Coaxial probe
- Ground Plane: PEC with low-loss dielectric

The simulation objective was to achieve precise resonance at 4.2 GHz, high efficiency, and stable far-field radiation, consistent with modern sub-6-GHz antenna design practices [11]

4. Results and Discussion

This section presents the simulated performance of the proposed cylindrical DRA. Results include S-parameters, impedance characteristics, radiation patterns, axial ratio response, and efficiency metrics, as illustrated in the accompanying figures.

4.1 S-Parameter and Impedance Analysis

The S11 response of the proposed antenna is shown in Figure 1(a), where a strong resonance is observed at 4.2 GHz with a minimum S11 of -37 dB. This deep return-loss notch indicates excellent impedance matching at the resonant frequency.

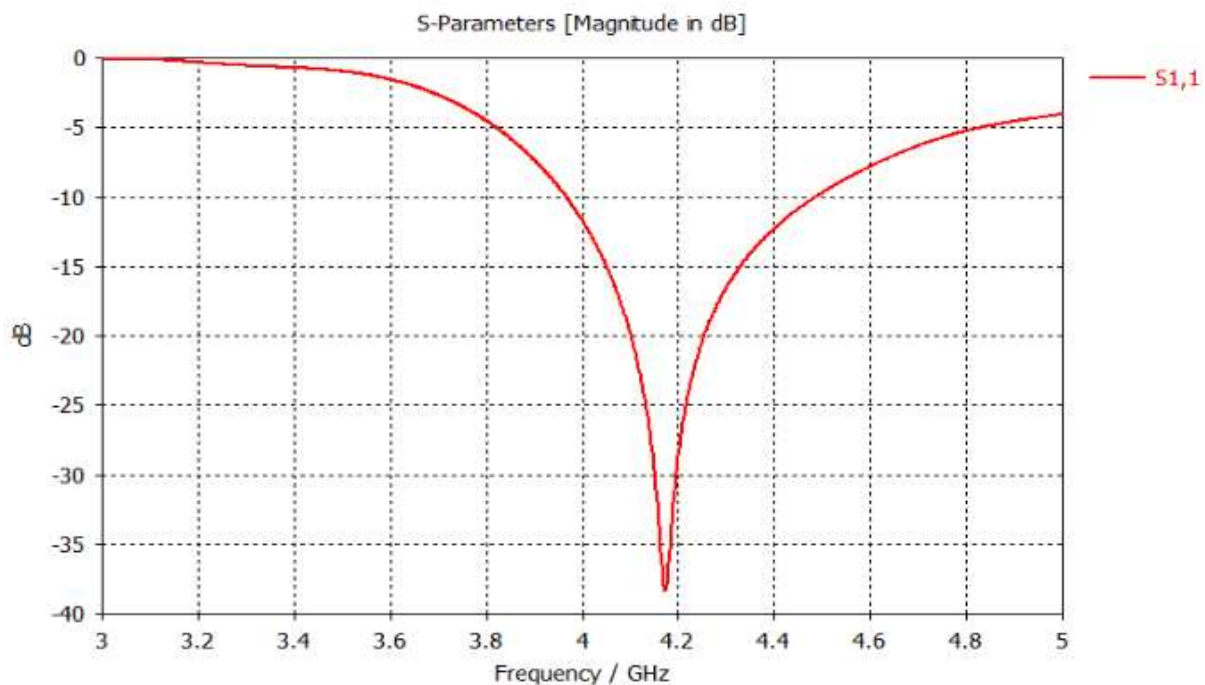


Figure 1(a). Simulated S11 curve

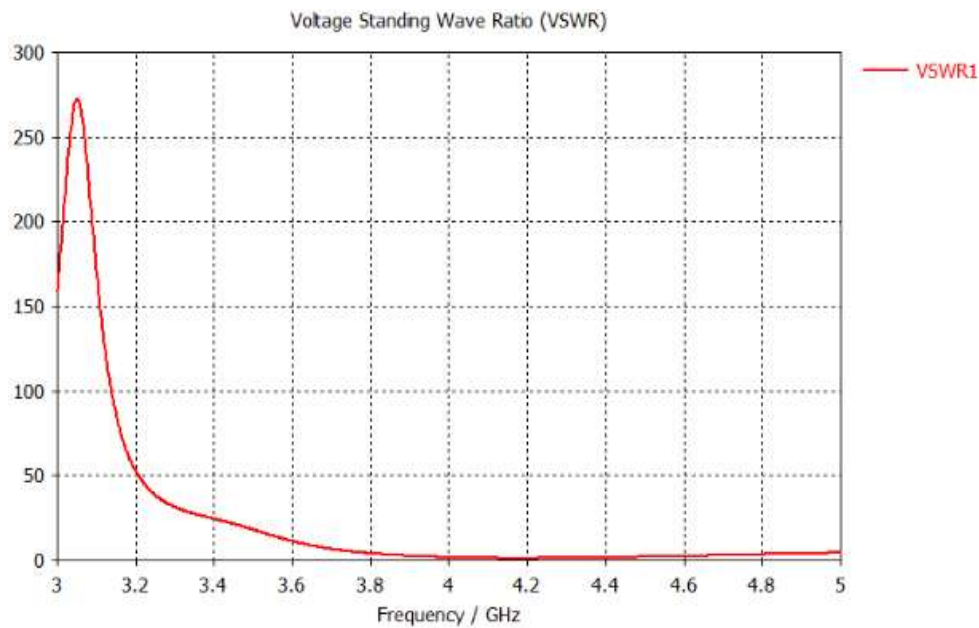


Figure 1(b). Simulated VSWR curve

The highly optimized matching behavior also highlighted by the VSWR shown by Figure 1(b). The value of VSWR obtained is 1.02 gives an idea how AI-assisted parametric design and tuning can accelerate the identification of optimum geometrical parameters, reducing power wastage and improving operational sustainability. Thus, the study demonstrates how AI-empowered antenna development can support the evolution of sustainable and energy-efficient power systems

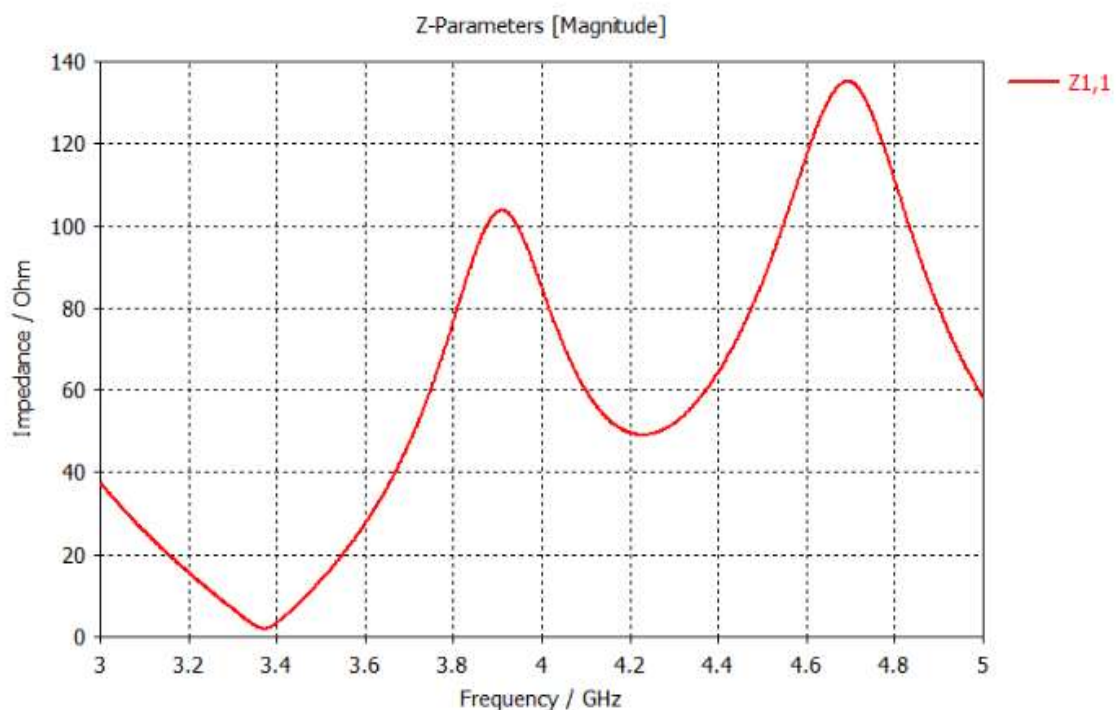


Figure 1(c). Simulated S11 curve

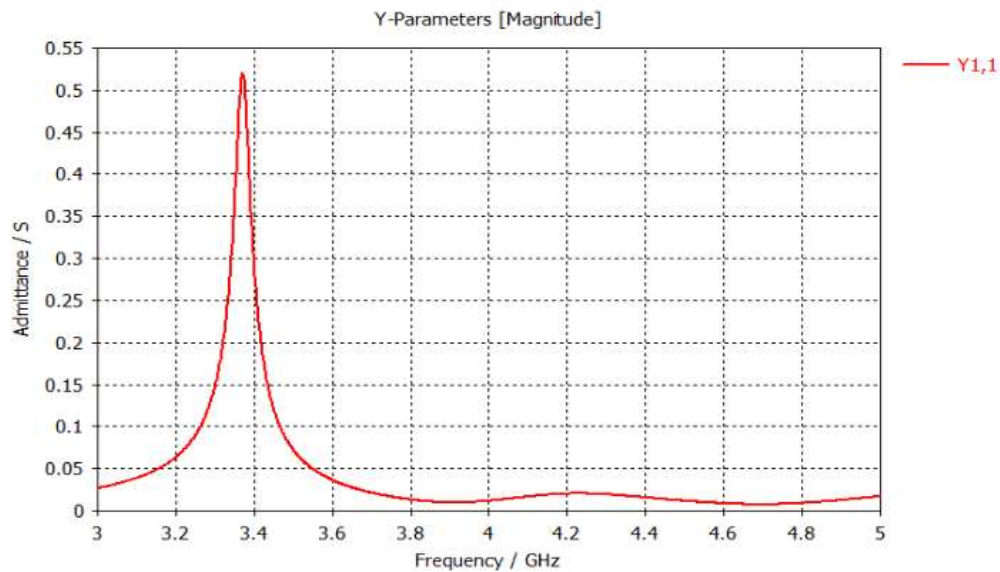


Figure 1(d). Simulated S11 curve

Furthermore, the Z11 and Y11 parameters (refer Figure 1(c) and (d)) validate resonance with a predominantly resistive input at 4.2 GHz and low reactive components, consistent with expected cylindrical DRA behavior. The stable impedance characteristics indicate that the antenna maintains predictable and reliable performance under varying operating conditions an essential requirement for intelligent, AI-assisted smart-energy systems. [13].

4.2 Radiation Characteristics

4.2.1 Directivity and Gain

The far-field directivity pattern, presented in Figure 2 (a) and far-field directivity presented in Figure 2 (b), shows a main-lobe directivity of 6.69 dBi at 4 GHz. The radiation pattern exhibits clean lobe formation with minimal sidelobes, demonstrating suitability for mid-range and indoor wireless deployments [14].

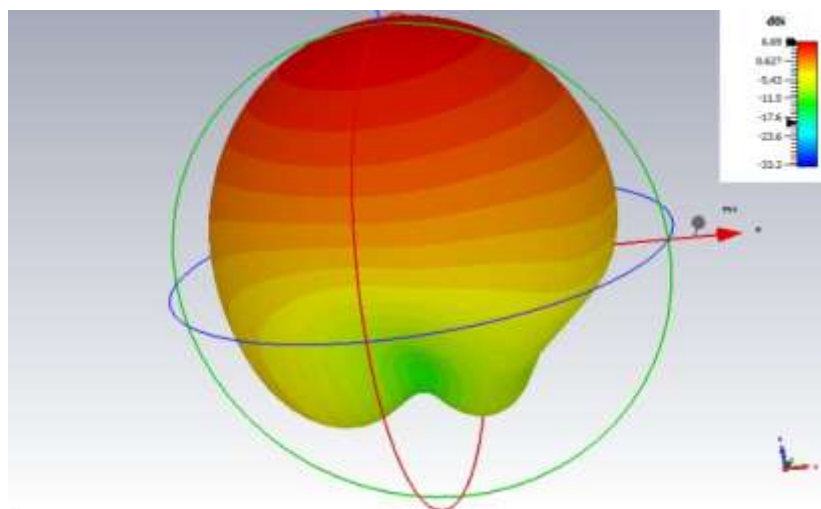


Figure 2 (a). 3D Far-field radiation pattern and

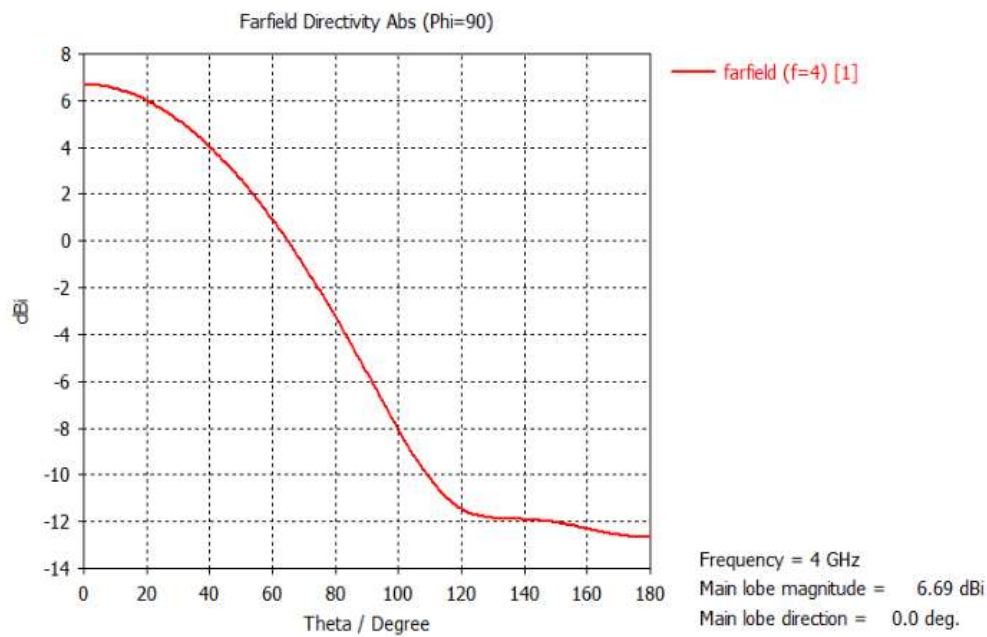


Figure 2 (b). Directivity polar plot

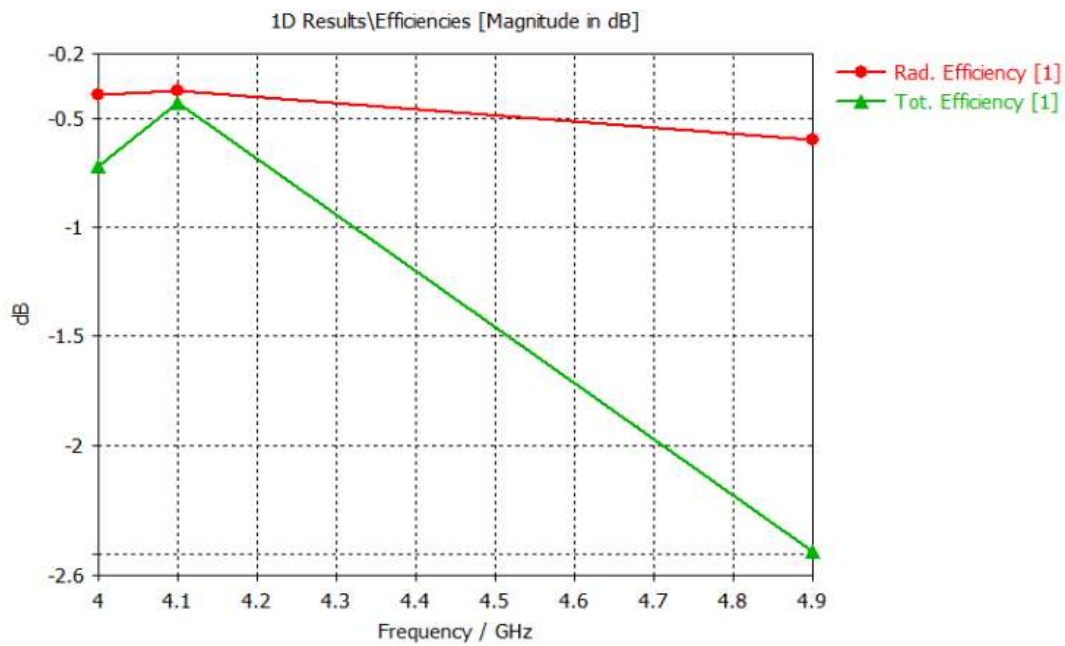


Figure 3. Radiation and Total efficiency plot

4.2.2 Radiated and Total Efficiency

The efficiency response, shown in Figure 3, indicates a radiation efficiency of -0.38 dB ($\sim 91\%$) and a total efficiency of -0.5 dB ($\sim 89\%$). These values confirm low dielectric and conductor losses, which are characteristic of optimized cylindrical DRAs [15].

4.2.3 Polarization and Axial Ratio

Figure 4. depict the axial-ratio (AR) plot which shows that the antenna exhibits linear polarization across most of the operating band. The AR reaches: Minimum AR ≈ 0 dB at $\theta \approx 160^\circ$, and Maximum AR ≈ 40 dB across other angular regions.

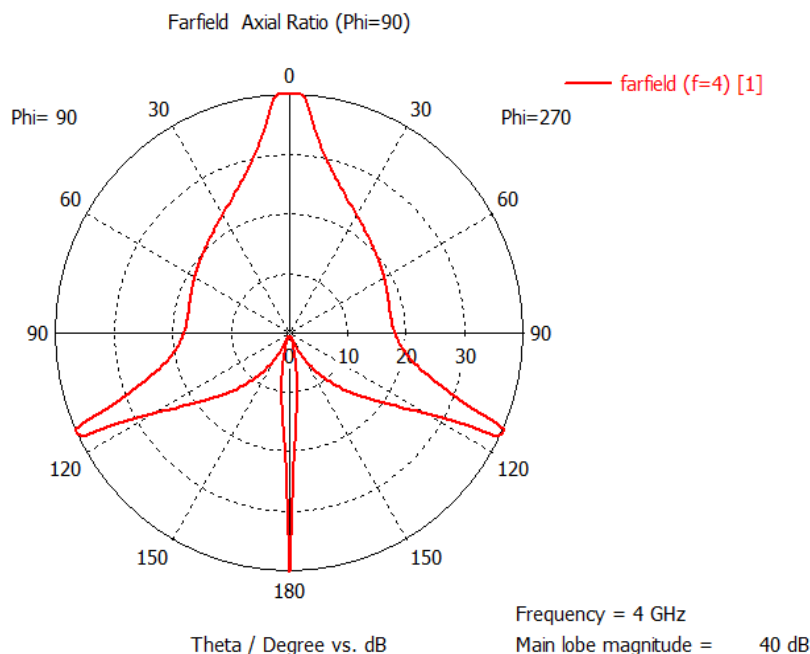


Figure 4. Axial Ratio Polar plot

5. Conclusion

In this work, a compact cylindrical Dielectric Resonator Antenna (DRA) operating at 4.2 GHz was designed and evaluated for sub-6-GHz 5G and IoT applications. The simulated results demonstrated excellent performance, with a minimum S11 of -37 dB, a VSWR of 1.02, and high radiation and total efficiencies of 91% and 89%, respectively. The antenna also exhibited a directivity of 6.69 dBi and a stable, nearly omnidirectional H-plane radiation pattern, confirming the suitability of the proposed structure for wide-coverage and mid-range communication scenarios. Impedance characteristics derived from Z11 and Y11 further validated strong resonance behavior and reliable mode excitation. The findings highlight that such cylindrical DRAs can achieve high performance while maintaining compact size and low material complexity. Moreover, by integrating AI-driven optimization strategies into the design workflow, the antenna development process can be significantly accelerated, enabling rapid exploration of parameter spaces with improved accuracy. This capability not only enhances antenna performance but also contributes to sustainable and energy-efficient system design, supporting the next generation of smart-grid, green-communication, and intelligent power-distribution frameworks.

6. Future Scope

The proposed design can be further enhanced using AI-driven multi-objective optimization to achieve wider bandwidth and improved polarization characteristics. Additionally, integrating

the antenna into smart-grid and IoT platforms can support the development of more sustainable, energy-efficient wireless communication systems.

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Conflict of Interest

The authors declare no conflict of interest.

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