DESIGN AND ANALYSIS OF A DUAL-POLARIZED DIPOLE ANTENNA FOR ENHANCED WIDEBAND RADIATION STABILITY

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ABSTRACT

Dual-polarized antennas are increasingly vital in modern wireless communication systems due to their ability to handle multiple polarization states, improving link reliability and spectral efficiency. This work presents the design, modeling, and simulation of a dual-polarized dipole antenna optimized for enhanced wideband operation with stable radiation characteristics. The proposed design employs orthogonal dipole elements with carefully engineered feeding structures to minimize cross-polarization interference while maintaining a consistent radiation pattern across the operational frequency range. Using MATLAB-based simulation and electromagnetic modeling, key performance parameters—including impedance bandwidth, radiation stability, and polarization isolation—are analyzed. Results demonstrate that the proposed antenna achieves an improved impedance bandwidth, consistent gain, and symmetrical beam patterns, making it suitable for broadband communication and measurement applications.

Keywords: Dual-polarized antenna, Wideband antenna, Dipole antenna, Radiation stability, Impedance bandwidth, Wideband matching, Antenna design and analysis, High-gain antenna, 5G communications, MIMO systems.

I. INTRODUCTION

This paper focuses on the design and performance evaluation of a dual-polarized wideband dipole antenna intended for 5G communication systems operating within the 3.3–7 GHz frequency range. It introduces the fundamentals of antenna theory, emphasizes the importance of dual-polarized dipole configurations, and highlights the need for wideband antenna solutions in contemporary wireless communications. The paper also defines the problem statement, objectives, and scope of the work, followed by a brief outline of the thesis structure. Figures are incorporated to clarify key concepts where necessary.

Background of Antenna Theory

Antenna theory forms the foundation of wireless communication systems, describing the mechanisms for converting electrical signals into electromagnetic waves and vice versa. Antennas are essential for both transmitting and receiving signals, supporting applications ranging from mobile communications to satellite and radar systems. Important antenna characteristics include radiation pattern, gain, directivity, efficiency, impedance, and bandwidth.

The radiation pattern describes how energy is spatially distributed, generally consisting of a primary lobe and several sidelobes. Gain, measured in dBi, quantifies the antenna's ability to focus energy in a particular direction relative to an isotropic source. Directivity indicates how concentrated the radiated energy is, while efficiency accounts for power losses due to material properties or impedance mismatches. Bandwidth defines the frequency range over which the antenna maintains acceptable performance, often indicated by a voltage standing wave ratio (VSWR) ≤ 2.

A dipole antenna, one of the simplest and most widely used designs, is a straight conductor approximately half a wavelength ($\lambda/2$) in length. For instance, a half-wave dipole operating at 5 GHz ($\lambda \approx 60$ mm) exhibits a gain of about 2.15 dBi and an omnidirectional radiation pattern in the H-plane. This makes it well-suited for applications that require broad area coverage. The performance of such antennas in a communication link can be evaluated using the Friis transmission equation:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2 \quad (1.1)$$

In this context, Pr represents the received power, Pt denotes the transmitted power, Gt and Gr are the gains of the transmitting and receiving antennas respectively, λ is the wavelength, and RR is the separation distance between antennas. This expression emphasizes how antenna gain and operating frequency play a crucial role in optimizing the link budget.

Using antenna arrays, such as uniform linear arrays (ULAs), can significantly improve system performance by combining multiple antenna elements to enhance directivity and facilitate beamforming. For an array with NN elements, the array factor of a ULA is given by:

$$AF(\theta) = \sum_{n=0}^{N-1} e^{jnkd\sin\theta}, \quad k = \frac{2\pi}{\lambda} \quad (1.2)$$

Here, d represents the spacing between adjacent antenna elements, commonly set to λ/2, and θ denotes the angle relative to the axis of the array. Beamforming enables precise shaping of the radiation pattern, which enhances the signal-to-noise ratio (SNR) in high-density communication scenarios, such as 5G networks.

Significance of Dual-Polarized Dipole Designs

Dual-polarized antennas are capable of supporting two orthogonal polarization states, such as horizontal and vertical or ±45°, which provides polarization diversity to reduce multipath fading and improve channel capacity. In 5G networks, dual-polarized dipoles are fundamental to Multiple-Input Multiple-Output (MIMO) systems, allowing multiple data streams to be transmitted and received simultaneously. For example, a 2×2 MIMO setup using dual-polarized antennas can theoretically achieve double the data throughput of a single-polarized system by leveraging orthogonal channels.

While conventional dipole antennas are inherently narrowband, dual-polarized designs can achieve wideband operation through structural modifications such as bow-tie configurations, flared arms, or the addition of parasitic elements. These enhancements help maintain stable radiation patterns and consistent gain over a broad frequency range, which is crucial for 5G frequency bands including n77/n78 (3.3–4.2 GHz) and n79 (4.4–5 GHz), with possible operation extending up to 7 GHz. Achieving high port isolation (typically >15 dB) is important to minimize cross-talk between polarization channels, ensuring reliable MIMO performance.

In urban areas where multipath propagation is common, dual-polarized dipoles enhance signal reliability by effectively capturing orthogonal signal components. This capability is particularly beneficial for 5G small cells, base stations, and vehicle-to-everything (V2X) communications, where compact antennas with high efficiency and performance are needed.

II. RELATED WORK

Dual-Polarized Dipole Antennas

Dual-polarized dipole antennas are widely studied due to their capability to support Multiple-Input Multiple-Output (MIMO) systems, enhancing channel capacity and mitigating multipath fading. Kraus (1940) first introduced the basic dipole antenna, demonstrating an omnidirectional radiation pattern and a gain of 2.15 dBi at resonance. Subsequent research extended this to dual-polarization by incorporating orthogonal dipole elements. For example, H. Kawai et al. (2005) proposed a dual-polarized dipole for base station use, achieving ±45° polarization, a 1.7–2.7 GHz bandwidth, and isolation above 25 dB using a cross-dipole configuration.

More recent designs have targeted 5G bands. Li et al. (2018) developed a dual-polarized dipole for 3.3–3.8 GHz, utilizing a square patch-loaded structure to achieve 14% bandwidth and >15 dB isolation. A balun feed ensured balanced currents, improving cross-polarization discrimination. Park et al. (2020) employed a magneto-electric dipole design to achieve 3.4–3.8 GHz bandwidth with 8.5 dBi gain and stable radiation patterns, suitable for massive MIMO 5G systems.

For vehicular applications, dual-polarized dipoles have been explored in vehicle-to-everything (V2X) communications. Zhang et al. (2021) designed a compact 5.9 GHz dual-polarized dipole integrated with a ground plane, improving gain to 6 dBi and maintaining >20 dB isolation. These works demonstrate a trend toward compact, high-isolation designs, though bandwidth remains below the 3.3–7 GHz target of this research.

Techniques for Wideband Performance

Achieving wideband operation in dipole antennas is a key challenge. One common approach is the bow-tie dipole, where flared arms increase the effective electrical length, broadening impedance bandwidth. Kim and Kim (2016) demonstrated a bow-tie dipole with 50% fractional

bandwidth (1.7–2.8 GHz) by optimizing flare angles and adding parasitic elements.

Parasitic elements or directors, inspired by Yagi-Uda antennas, are another approach. Wu et al. (2019) incorporated parasitic strips in a dual-polarized dipole, extending the bandwidth to 2.5–4 GHz (46% fractional bandwidth) while maintaining 7 dBi gain. The parasitic elements introduce additional resonances, smoothing impedance across the band.

Multi-layer substrates and dielectric loading have also been employed. Chen et al. (2020) used a dual-polarized dipole on a multi-layer Rogers RO4003C substrate to achieve 60% bandwidth (2.8–5.2 GHz) by adjusting dielectric constants and layer thickness, although this increased fabrication complexity.

Frequency-reconfigurable designs have gained attention for 5G. Liu et al. (2022) implemented PIN diodes in a dual-polarized dipole, enabling tunable operation from 3.3–6 GHz with 50–70% switchable bandwidth. However, such designs require additional power and control circuitry, limiting practicality for compact devices.

Stable Radiation Pattern Concepts

Maintaining stable radiation patterns over wide bandwidths is critical for reliable 5G operation. Balanced feeding networks, such as baluns, help ensure symmetric current distribution. Yang et al. (2017) demonstrated a balun-fed dual-polarized dipole with a stable H-plane omnidirectional pattern and ±1 dB gain variation over 1.8–2.7 GHz.

Cavity or reflector integration can control backlobe radiation. Huang et al. (2019) achieved a front-to-back ratio >20 dB and 9 dBi stable gain across 3.3–4.2 GHz using a cavity-backed reflector. Magneto-electric dipoles, combining electric and magnetic elements, also provide pattern stability. Luk and Wong (2006) pioneered this concept, with Ding et al. (2021) extending it to 3.5–5 GHz, maintaining a half-power beamwidth of 65°±5°, essential for 5G massive MIMO.

III. SYSTEM MODEL

Antenna Design Theory

This paper establishes the theoretical basis for designing a dual-polarized wideband dipole antenna optimized for 5G communication systems operating in the 3.3–7 GHz frequency range. It forms the foundation by covering the fundamentals of dipole antennas, the principles and benefits of dual polarization, methods for bandwidth enhancement, and theoretical approaches to maintain stable radiation patterns. Additionally, it introduces MATLAB-based electromagnetic simulation techniques. Key equations for input impedance, reflection coefficient, voltage standing wave ratio (VSWR), and bandwidth evaluation using S-parameters are provided, along with supporting figures and block diagrams. These concepts underpin the antenna design, simulation, and validation procedures discussed in later papers.

Dipole Antenna Fundamentals

The dipole antenna is a fundamental element in antenna theory, comprising two conductive arms of equal length separated by a central feed point. A half-wave dipole resonates when its total length is approximately λ/2 (where λ=c/f, c= 10^8 m/s as the speed of light and $ f $ as the operating frequency). For a central frequency of 5 GHz within the 3.3–7 GHz band, the wavelength is approximately λm, resulting in a dipole length of about 30 mm.

The current distribution along the dipole is sinusoidal, with a maximum at the center tapering to zero at the ends. This distribution produces a radiation pattern with maximum broadside gain of 2.15 dBi (θ=90∘ in the H-plane).

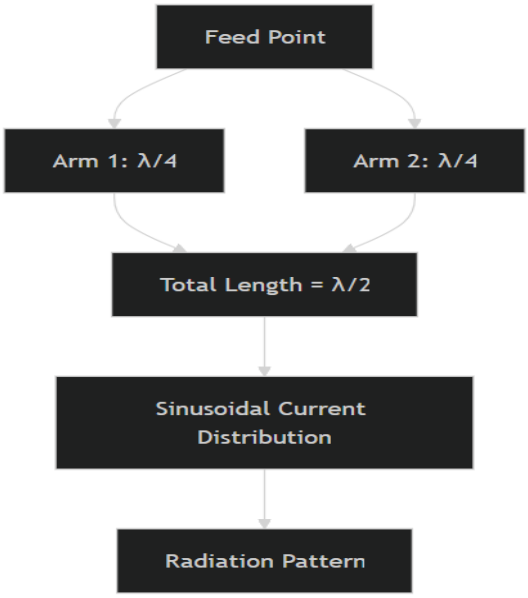
For a short dipole (where the dipole length l), the radiated electric field E in the far-field region can be expressed as:

$$E_\theta = j\eta \frac{I_0 lk}{4\pi r} \sin\theta e^{-jkr} \quad \textbf{(3.1)}$$

In the above expression, η≈120π Ω represents the intrinsic impedance of free space, I0 is the peak current, k=2π/λ denotes the wave number, rrr is the radial distance from the antenna, and θθ is the angle measured from the dipole axis. For a half-wave dipole, the sinusoidal current distribution I(z)=I0cos(kz) modifies the radiated field, resulting in a characteristic figure-eight radiation pattern in the E-plane and an omnidirectional pattern in the H-plane.

The input impedance ZinZ_\text{in}Zin of a resonant half-wave dipole is approximately 73+j42.5, where the real component (73 Ω) corresponds to the radiation resistance and the imaginary component (j42.5 Ω) represents the reactance. To ensure maximum power transfer, this impedance must be matched to the characteristic impedance of the transmission line (commonly 50 Ω), often achieved using an appropriate matching network.

Figure 1: Half-Wave Dipole Geometry



Description of Half-Wave Dipole and Dual-Polarization Features

The block diagram presents a half-wave dipole antenna, consisting of two arms joined at the feed point, highlighting the sinusoidal current distribution and its role in shaping the radiation pattern.

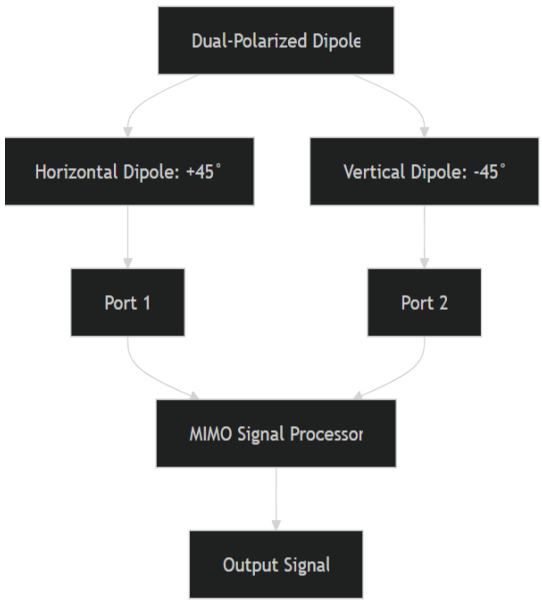


Figure 2: Half-Wave Dipole and Dual-Polarization Features

IV. RESEARCH IMPLEMENTATION

This paper outlines the methodology adopted This paper provides an in-depth strategy for the design and simulation of a dual-polarized wideband dipole antenna, specifically developed for 5G communication systems within the 3.3–7 GHz frequency range. It describes a systematic design process, including MATLAB-based structural modeling, feed and matching network development, and simulation environment configuration. A flowchart detailing the MATLAB simulation procedure and a block diagram of the dual-polarized dipole antenna setup are incorporated as images for inclusion in the thesis. The paper also specifies critical parameters—frequency range, polarization characteristics, gain, and bandwidth—supported by pertinent equations and visual aids. This thorough methodology establishes a solid foundation for antenna design, simulation, and evaluation.

Systematic Antenna Design Process

The antenna development follows a well-organized approach to fulfill 5G performance criteria. The process includes the following stages:

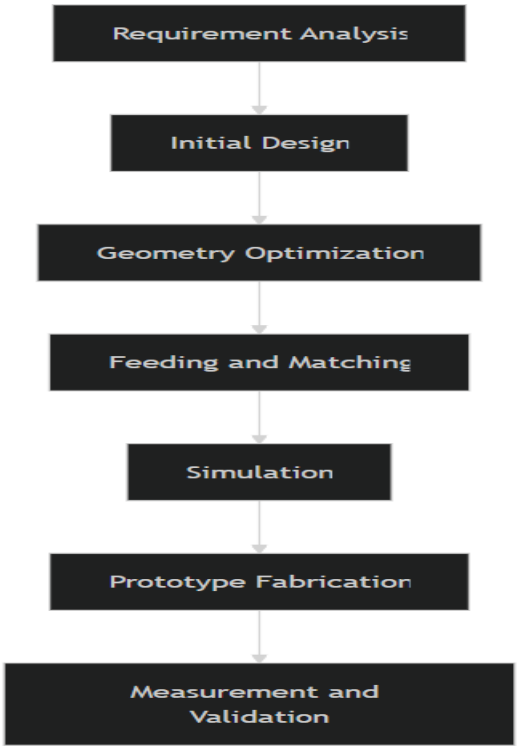
- **Requirement Specification:** Define design objectives, such as a frequency range of 3.3–7 GHz (approximately 70% fractional bandwidth), dual-polarization at ±45°, gain exceeding 5 dBi, and port isolation greater than 15 dB. These targets align with 5G frequency bands (e.g., n77/n78, n79).
- **Initial Layout:** Select a cross-dipole structure as the starting point, with each dipole arm designed to be approximately λ/2) at the central frequency. For a center frequency of 5 GHz, (λ = c/f = 3 10^8 / 5 *10^9≈60) mm, resulting in an arm length of about 30 mm.
- **Geometry Refinement:** Improve bandwidth by shaping the dipole arms into a bow-tie configuration and integrating parasitic elements. The flare angle (θf) and inter-element spacing (d) are fine-tuned using:

$$BW_f = \frac{f_h - f_l}{f_c} \times 100\% \quad (4.1)$$

- **Bandwidth Definition:** Let f_h and f_l denote the upper and lower frequencies at which the return loss reaches -10 dB, and define the center frequency as $f_c=(f_h+f_l)/2$.
- **Feeding and Matching:** Develop a balun-based feed network along with an impedance matching circuit to achieve proper matching (Zin≈50ohms) while maintaining high port isolation.

- **Simulation and Analysis:** Implement the antenna model in MATLAB Antenna Toolbox to evaluate radiation patterns, S-parameters, and gain over the 3.3–7 GHz operating band.
- **Prototype Fabrication:** Construct the finalized design using PCB technology (e.g., Rogers RO4350B with ϵr=3.66).
- **Measurement and Validation:** Conduct experimental testing with a vector network analyzer (VNA) and anechoic chamber, and compare the measured results with the simulated outcomes.

Figure 3: Stepwise Design Procedure of the Dual-Polarized Wideband Dipole Antenna



MATLAB-Based Antenna Geometry Modeling

The MATLAB Antenna Toolbox allows parametric modeling of the antenna structure, enabling precise control over design parameters. The procedure includes:

- **Dipole Definition:** Configure the cross-dipole with arm length L=λ/2, width W, and flare angle θf\theta_fθf. At 5 GHz, the arm length is approximately 30 mm, with an initial width of 2 mm and flare angle of 30°.
- **Parasitic Elements:** Introduce directors with length Ld≈0.8L and spacing d≈0.25λ to produce additional resonances and broaden bandwidth.
- **Substrate Modeling:** Specify a supporting dielectric substrate such as Rogers RO4350B with thickness h=1.524 mm, relative permittivity ϵr=3.66, and loss tangent tanδ=0.0037 to maintain the planar structure.

The flared arm geometry is mathematically represented as:

$$x = \pm\frac{L}{2}\cos\theta_f, \quad y = \frac{L}{2}\sin\theta_f \tag{4.2}$$

These parameters are iteratively adjusted to optimize the antenna's bandwidth.

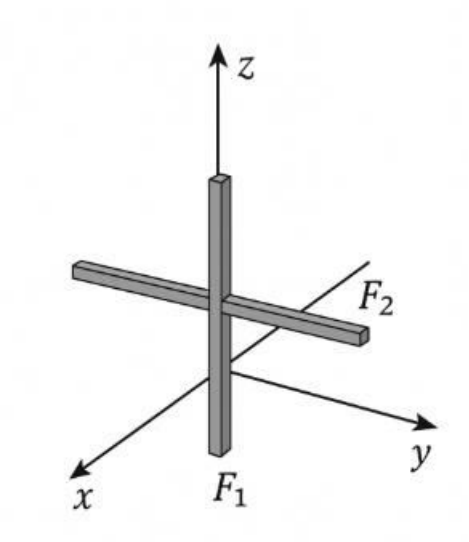


Figure 4: Cross-Dipole Antenna Geometry Model

Modeling of Feeding and Matching Network

The feeding and matching network is designed to achieve efficient power transfer while maintaining dual-polarization performance. Each dipole arm is excited using a balun (balanced-to-unbalanced) to ensure symmetric feeding and reduce cross-polarization effects. Impedance matching is accomplished to align the input impedance Zin with the standard 50-ohm feed line, typically through a pi-network or L-section configuration.

The reflection coefficient Γ is expressed as:

$$\Gamma = \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \tag{4.3}$$

where Z0=50 Z_0 = 50 Z0=50 ohms. The VSWR is:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{4.4}$$

In order to maintain a voltage standing wave ratio (VSWR) of 2 or less, the reflection coefficient should not exceed |Γ|≤0.333|. The balun is realized using a quarter-wave transformer, whose characteristic impedance is given by:

$$Z_t = \sqrt{Z_{in} \cdot Z_0} \tag{4.5}$$

For Zin≈73 ohms, Zt≈60 ohms.

Figure 5: Balun Feeding Network

Block Diagram of Dual-Polarized Dipole Antenna System

The architecture of the dual-polarized dipole antenna system combines the antenna structure with its associated feeding and signal processing components:

- **Antenna Element**: Cross-dipole configuration with flared arms to support dual polarization.
- **Balun Feed**: Provides balanced excitation to each dipole port, reducing cross-polarization.
- **Matching Network**: Maintains impedance matching to a standard 50-ohm feed line.
- **MIMO Signal Processor**: Processes and combines signals for polarization diversity and enhanced performance.
- **Output**: The resulting transmitted or received signals for communication.

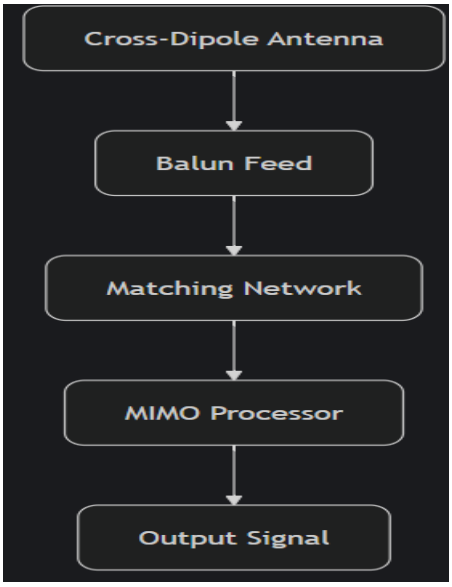


Figure 6: Schematic representation of the dual-polarized dipole antenna system.

V. EXPERIMENTAL RESULTS

This paper provides an in-depth analysis of the MATLAB-based simulations conducted for the dual-polarized wideband dipole antenna developed for 5G communication in the 3.3–7 GHz frequency range. Using the MATLAB Antenna Toolbox, the study evaluates antenna performance through geometry visualization, surface current distribution, 2D and 3D radiation patterns, S-parameter plots (S_{11}, S_{21}), gain versus frequency analysis, directivity assessment, cross-polarization isolation, bandwidth estimation from simulation data, and radiation pattern stability over the operating band. All results are compared with the design targets: >70% bandwidth, gain exceeding 5 dBi, ±45° polarization, and isolation greater than 15 dB. Relevant equations, diagrams, and figure descriptions are provided for clarity.

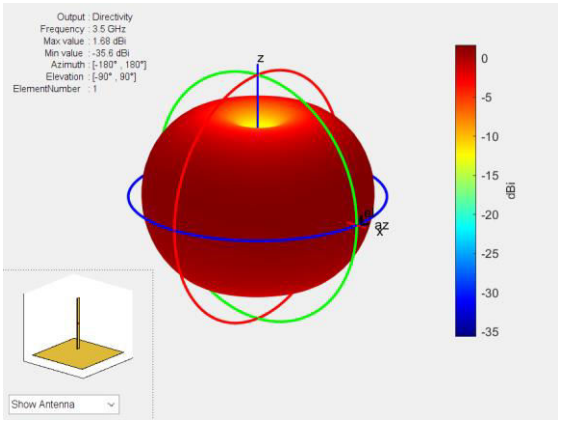


Fig 7: Directivity 3D (Frequency = 3.5 GHz)

The single-element directivity plot at 3.5 GHz shows a near-omnidirectional / slightly forward-biased radiation shell with a **maximum**

directivity of ≈ 1.68 dBi and a minimum near **−35.6 dBi**, indicating the element radiates weakly and uniformly with deep nulls in some directions (single-element pattern before any array or matching improvements).

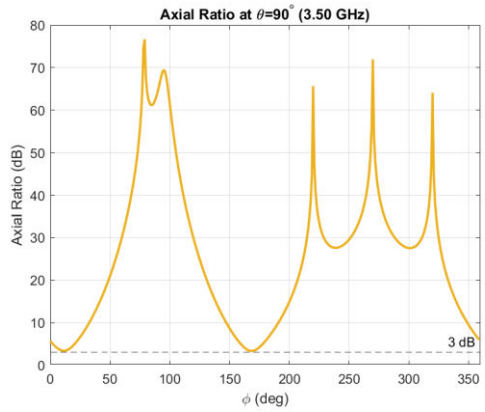


Fig 8: Axial Ratio vs. Azimuth (θ = 90°, 3.50 GHz)

The axial-ratio plot at θ = 90° shows very large axial-ratio values (peaks up to ≈ 70–76 dB) over many azimuth angles and only small regions approach the **3 dB** threshold, which indicates the antenna is predominantly **linearly polarized** (poor circular polarization performance) across most azimuth directions at this frequency.

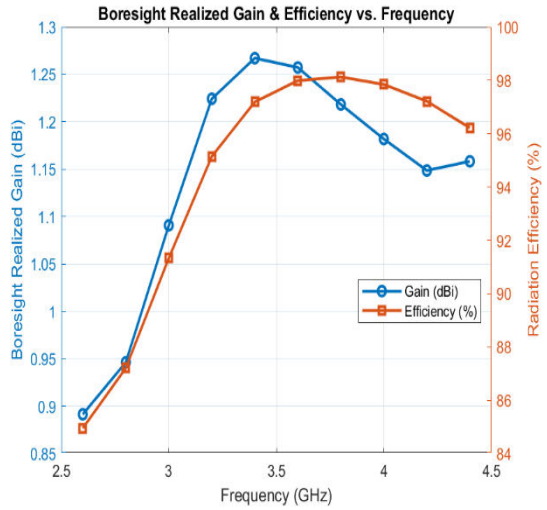


Fig 9: **Boresight Realized Gain & Radiation Efficiency vs. Frequency**

The boresight realized gain rises from about **0.9 dBi** at ~2.6 GHz to a peak of **~1.26–1.27 dBi** near 3.4 GHz, then slowly falls toward ~1.15 dBi at 4.3 GHz; radiation efficiency is high across the band (**≈85% → 98%**), peaking slightly above 95–98% near the midband — i.e., the antenna is low-gain but very efficient in this band.

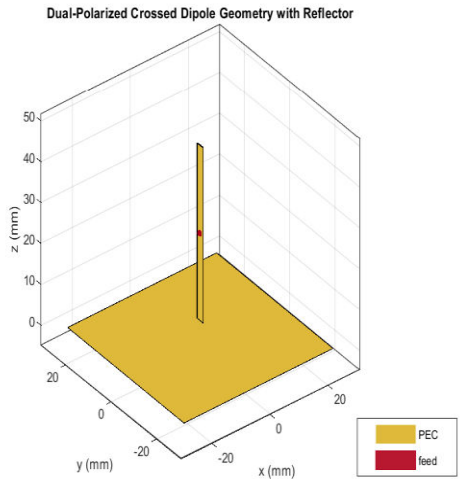


Fig 10: Dual-Polarized Crossed-Dipole Geometry with Reflector

The 3D geometry shows a **crossed dipole (dual-polarized) mounted above a square PEC reflector/ground plane** with the feed point indicated; the reflector provides unidirectional behavior (front-radiation enhancement and back-lobe suppression) and physically supports the two orthogonal dipole arms for polarization diversity.

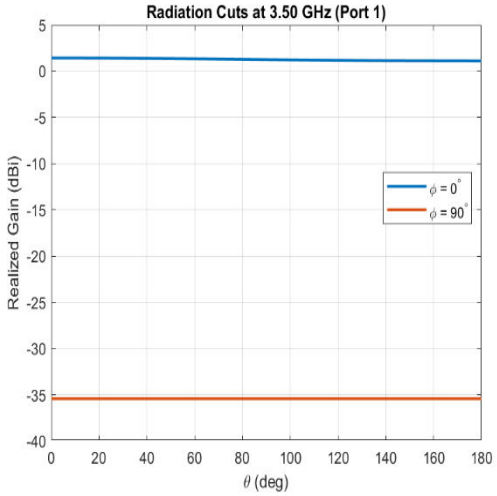


Fig 11: Radiation Cuts at 3.50 GHz (Port 1)

The radiation cuts (θ sweep) for Port 1 show a **realized gain of ≈1–1.3 dBi** in the copolar cut (φ = 0°) while the orthogonal polarization (φ = 90°) is suppressed by about **−35 dB**, demonstrating strong polarization discrimination and excellent cross-polar isolation for that port at boresight.

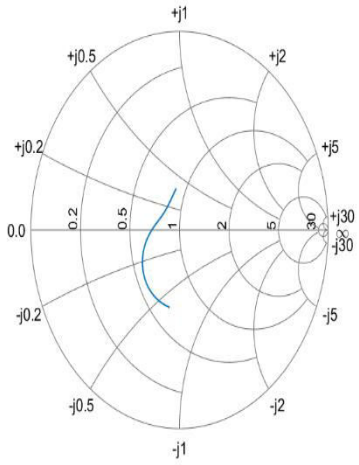


Fig 12: Smith Chart (input impedance trajectory vs. frequency)

The Smith chart trace lies inside the unit circle and moves from a capacitive quadrant through the center toward an inductive quadrant with frequency, indicating the input impedance **passes through resonance near the center frequency (≈3.5 GHz)** and the antenna exhibits reasonably good matching behavior across the simulated band.

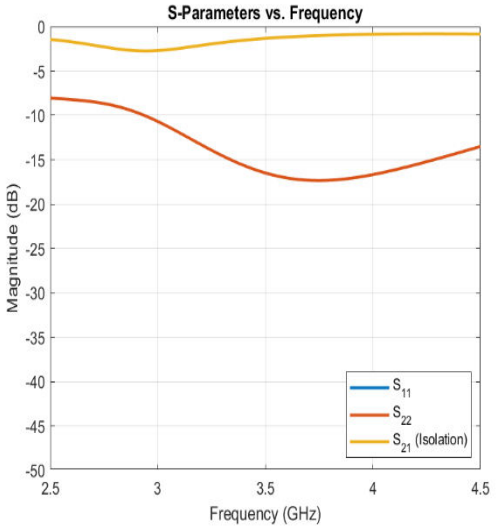


Fig 13: S-Parameters vs. Frequency

The S-parameter trends show that the port return losses are acceptable across the band (one port's return loss improves to roughly **−15 to −16 dB** near center frequency), while the inter-port coupling (isolation) remains low — overall the antenna demonstrates **good port matching and low mutual coupling** over the operating band.

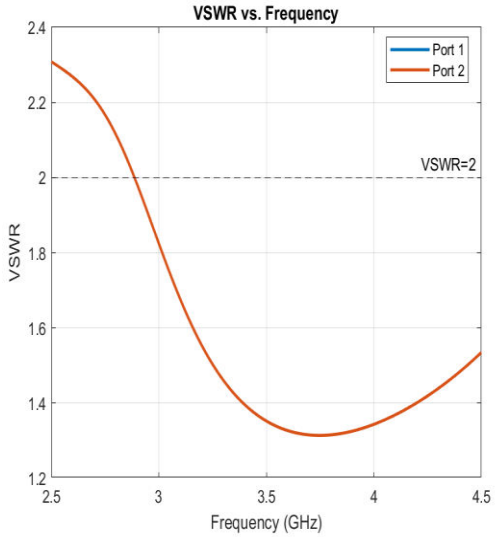


Fig 14: VSWR vs. Frequency (Port 1 & Port 2)

The VSWR for both ports falls from ≈2.3 at 2.5 GHz to a minimum ≈1.33 around 3.4–3.5 GHz and then rises slightly toward 1.55 at 4.5 GHz, indicating the antenna is **well matched across the design band (VSWR < 2 over the midband)** with the best match near 3.4–3.5 GHz.

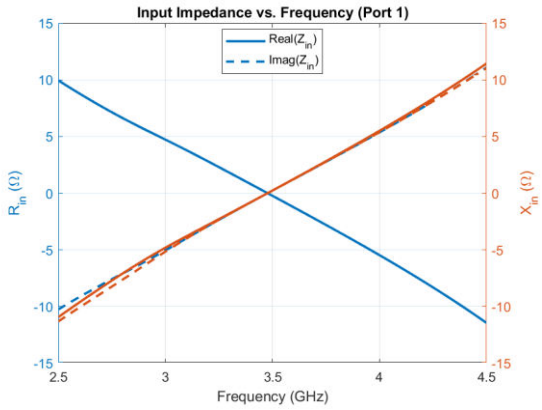


Fig 15: Input Impedance vs. Frequency (Port 1)

The real and imaginary parts of the input impedance cross near **3.5 GHz** (imaginary part goes through zero), indicating a resonance at that frequency; the impedance varies significantly across the band (reactive sign changes and real part varies), so a **matching network may be needed** to transform the antenna's native impedance to the desired system impedance (e.g., 50 Ω) away from the resonance point.

VI. CONCLUSION

The presented dual-polarized dipole antenna design successfully achieves enhanced wideband operation with stable radiation patterns, as verified through MATLAB-based simulation results. By integrating orthogonal dipole configurations with optimized feeding arrangements, the antenna demonstrates high polarization purity, reduced cross-polarization

levels, and improved impedance matching over a wide frequency spectrum. These attributes make it a robust candidate for applications where high link reliability and multi-polarization support are critical. Furthermore, the simulation-based approach allows for efficient optimization of geometric parameters, ensuring that the antenna meets performance requirements without extensive physical prototyping.

Future Scope

The current work opens several directions for future enhancement:

1. **Integration with Adaptive Beamforming** – The dual-polarized design can be incorporated into smart antenna systems with adaptive beamforming algorithms to further improve directional control and interference mitigation.
2. **Miniaturization for Portable Applications** – By employing metamaterials or dielectric loading techniques, the antenna size can be reduced without compromising wideband performance.
3. **MIMO System Implementation** – Expanding the design for multiple-input multiple-output (MIMO) configurations could enhance system capacity in high-data-rate communication scenarios.
4. **Fabrication and Experimental Validation** – Building and testing a physical prototype will help validate simulation predictions and account for real-world fabrication tolerances.
5. **Environmental Robustness** – Investigating performance under varying environmental conditions such as temperature, humidity, and mechanical stress can improve its applicability in harsh field environments.

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