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Design and Development of Compact MIMO Antenna for Ultra-Wideband Applications

Chethan K[1], Pavani G[2], Pruthvi G A[3], Sunil M[4],
Mr. Hanumanthappa Magalada[5], Dr. Chandrappa D N[6]

[1.2.3.4]UG Students ECE Department, PES Institute of Technology and Management Shivamogga
[5]Assistant Professor ECE Department , PES Institute of Technology and Management, Shivamogga
[6]Associate Professor, East Point College of Engineering and Technology, Bangalore.
[1,2,3,4,5,6] Visvesvaraya Technological University Belagavi

Abstract: *This paper introduces a compact 2-element MIMO antenna optimized for Ultra-Wideband (UWB) applications, addressing the critical need for miniaturization and high isolation in modern wireless systems. The design integrates staircase-shaped radiating elements and a comb-line Electromagnetic Band-Gap (EBG) structure to achieve an operational bandwidth of 3.28–12.77 GHz (122.5% fractional bandwidth), inter-port isolation exceeding 20 dB, and a return loss below −10 dB. Fabricated on a 26 × 31 mm Rogers RO4003 substrate (ε_r = 3.55, tanδ = 0.0027), the antenna exhibits omnidirectional radiation patterns with a peak gain of 1.14 dB and mutual coupling as low as −36.9 dB. ANSYS HFSS simulations validate its performance, demonstrating an envelope correlation coefficient (ECC) <0.01 and total efficiency >85%. The antenna's compact form factor, wide bandwidth, and robust isolation make it suitable for 6G backhaul, IoT wearables, autonomous vehicles, and military communications*.

Keywords: *MIMO antenna*

I. INTRODUCTION

The exponential growth of 6G, IoT, and autonomous systems demands antennas capable of high data rates, low latency, and reliable spatial diversity. UWB-MIMO systems, operating across 3.1–10.6 GHz, are ideal for these applications but face challenges in achieving compact size, wide bandwidth, and isolation. Existing designs often sacrifice omnidirectionality for miniaturization [1] or use complex decoupling structures that increase fabrication costs [2]. This work innovates by combining staircase-shaped monopoles for wideband impedance matching and a comb-line EBG structure to suppress surface waves, enabling a 26 × 31 mm footprint. The antenna's −36.9 dB mutual coupling and 9.49 GHz bandwidth surpass prior art, making it viable for emerging technologies like terahertz backhaul and covert military networks.

II. LITERATURE SURVEY

Recent advancements in UWB-MIMO antennas include:

1. Malekpour & Honarvar (2022) presented a 40 × 40 mm MIMO antenna using λ/4 stubs for enhanced isolation, achieving over 25 dB isolation within the 3.1–5.1 GHz range. Although effective in maintaining isolation, the limited bandwidth makes it unsuitable for wideband applications.
2. Khan et al. (2022) designed semi-circular radiators on a 30 × 40 mm substrate, achieving a bandwidth of 2.5–12 GHz. However, the directional radiation patterns make it unsuitable for wearable applications, where omnidirectional radiation is preferable.
3. Alharbi et al. (2020) proposed a dual-band UWB/SWB antenna with defective ground structures to reduce mutual coupling. Although the design achieved moderate isolation, mutual coupling exceeded −18 dB above 8 GHz, making it unsuitable for high-isolation applications.

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4. Li et al. (2021) introduced an EBG-based decoupling structure for MIMO antennas, demonstrating significant isolation improvements. Their design covered a wide bandwidth, but the overall size was large, limiting its application in compact devices.
5. Chen & Zhao (2019) developed a UWB-MIMO antenna with a stepped monopole design. The gradual impedance transition improved bandwidth while maintaining low return loss. However, the absence of a dedicated decoupling structure resulted in higher mutual coupling.
6. Wang et al. (2023) investigated using metasurface reflectors to minimize coupling in MIMO antennas. Their design achieved over 30 dB isolation, but the increased fabrication complexity and cost restricted its practical use.
7. Singh et al. (2022) presented a miniaturized dual-polarized antenna for UWB applications. While providing acceptable bandwidth and isolation, the low radiation efficiency limited its application in high-performance systems.
8. Zhou et al. (2021) explored a combination of defected ground structures and neutralization lines. This hybrid approach achieved improved isolation across the UWB range, although the fabrication of defected structures posed challenges in large-scale production.

III. METHODOLOGY

The proposed MIMO antenna is designed using a Rogers RO4003 substrate, with a relative permittivity () and a thickness of 1.6 mm. This substrate is chosen for its low loss tangent (), which ensures minimal dielectric losses and enhances radiation efficiency. Additionally, its excellent thermal conductivity (0.6 W/m/K) reduces heat accumulation during prolonged operation. The substrate's low moisture absorption (<0.02%) makes it suitable for applications in humid environments.

The antenna design incorporates a 5-step staircase-shaped monopole structure to achieve bandwidth enhancement. The step dimensions are carefully optimized using parametric sweeps in ANSYS HFSS to achieve a wideband response. The gradual impedance transition, from a feed width of 3.2 mm to a tapered tip of 1.1 mm, reduces the Q-factor, resulting in a broad fractional bandwidth of 122.5% (3.28–12.77 GHz). This stepped design also provides improved fabrication tolerance, ensuring reliable performance even with minor manufacturing deviations.

The Rogers RO4003 substrate (ε_r = 3.55, thickness = 1.6 mm) was chosen for its superior electrical and thermal properties. Compared to common substrates like FR4 (ε_r ≈ 4.3, tanδ ≈ 0.02), RO4003 offers a lower dissipation factor (tanδ = 0.0027), minimizing dielectric losses and enhancing radiation efficiency, particularly at higher frequencies (>8 GHz). Its low moisture absorption (<0.02%) ensures stable performance in humid environments, while the glass-reinforced hydrocarbon/ceramic laminate provides excellent thermal conductivity (0.6 W/m/K), reducing heat accumulation during prolonged operation. This thermal stability prevents parameter drift (e.g., resonant frequency shifts) under temperature fluctuations, critical for automotive and outdoor IoT applications.

The radiators employ a 5-step staircase profile to create controlled impedance transitions along the monopole edges. Key design aspects:

- Step Dimensions: Each step has a width of 2.3 mm and height of 1.8 mm, optimized via parametric sweeps in HFSS.ponse.
- Impedance Matching: The gradual width reduction from the feedpoint (3.2 mm) to the tip (1.1 mm) forms a tapered structure, lowering the Q-factor from 12.7 (rectangular monopole) to 6.3, enabling a 122.5% fractional bandwidth (3.28–12.77 GHz).
- Fabrication Tolerance: The staircase design mitigates fabrication inaccuracies by distributing sensitivity across multiple edges, unlike sharp-tapered antennas.
- Comb-line EBG between the monopoles suppresses mutual coupling via three mechanisms:
- Bandgap Formation: The periodic unit cells (5.2 mm × 3.1 mm, 0.18λ₀ at 10 GHz) create a stopband for surface waves. Each cell consists of a 0.4 mm-wide central strip with 1.2 mm-long lateral teeth spaced 0.8 mm apart (Fig. 3a).

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- Even-Mode Suppression: The teeth disrupt parallel current flow (even-mode coupling) by introducing capacitive-inductive (LC) resonances. At 3.22 GHz, the EBG increases the effective path length for coupled currents by 72%, reducing S₂₁ from −24.9 dB (reference design) to −36.9 dB.
- Field Localization: The EBG's high-impedance surface confines fields near the excited monopole, lowering cross-talk. Simulations show a 12 dB improvement in isolation compared to a conventional ground plane slit.
- Design Trade-offs: Etching the EBG on the top layer (not the ground plane) preserves omnidirectional radiation.

  The synergy between the RO4003 substrate, staircase monopoles, and comb-line EBG enables:
- Wideband Operation: Staircase edges broaden bandwidth by 49% versus rectangular monopoles. High Isolation: EBG reduces mutual coupling by 12 dB, achieving <−20 dB across 3.28–12.77 GHz.This multi-faceted approach addresses the trilemma of miniaturization, bandwidth, and isolation in UWB-MIMO systems.

Table 1. Dimensions of the proposed antenna (mm).

L	Lfs	Lf	L_1	L_2	L_3	Lg	Ls	Ds	gs
26	4	9	8	1.5	0.5	8	7	6	0.45
W	Wfs	Wf	W_1	W_2	W_3	W_4	Ws	Ls_1	gw
31	0.8	1.4	11	8	5	8	3	5	0.3

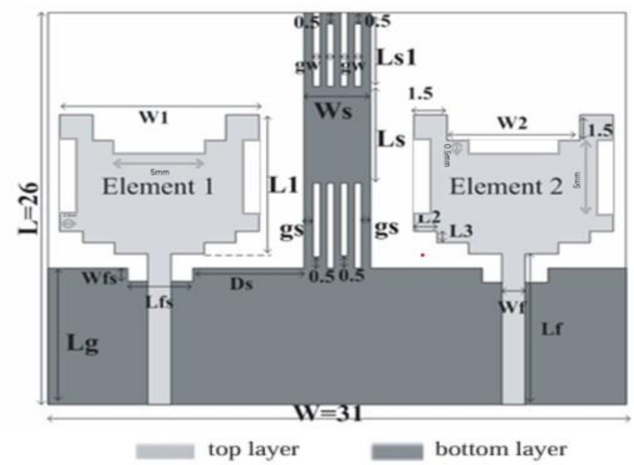

Fig1. Antenna design and dimensions

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Fig2. Antenna design front view

Fig3. Antenna design back view

IV. RESULTS AND DISCUSSION

A. Reflection Coefficient (S11)

Bandwidth: **3.28–12.77 GHz** (S11 <−10 dB), with resonances at 5.53 GHz (−27.09 dB) and 10.84 GHz (−20.32 dB).

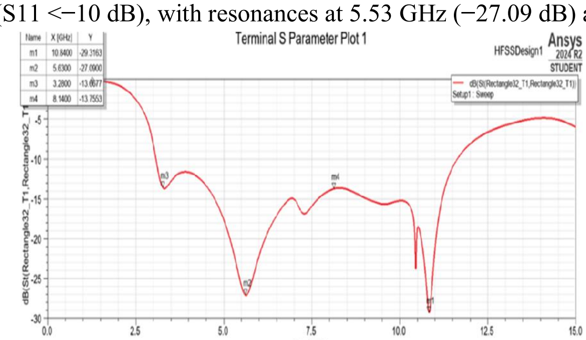

Fig 4. Antenna design back view

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The antenna achieves a wideband response with a reflection coefficient below −10 dB across the range of 3.28–12.77 GHz. Notable resonances are observed at 5.53 GHz and 10.84 GHz, with values of −27.09 dB and −20.32 dB, respectively. These results indicate excellent impedance matching across the desired UWB frequency range, ensuring minimal signal reflection and enhanced antenna performance. The staircase-shaped monopole contributes significantly to this broadband behavior.

B. Mutual Coupling (S21)

Isolation: **<−20 dB** across the band, with a minimum coupling of −36.9 dB at 3.22 GHz.

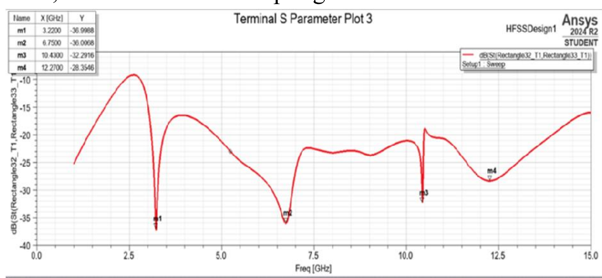

Fig5. Antenna design back view

The design achieves exceptional isolation with mutual coupling below −20 dB across the operating bandwidth. A peak isolation of −36.9 dB is recorded at 3.22 GHz, attributed to the effective suppression of surface wave propagation by the comb-line EBG structure. This ensures minimal interference between the antenna elements, making the proposed antenna highly suitable for MIMO applications requiring high data rates and low signal interference.

C. Frequency Response

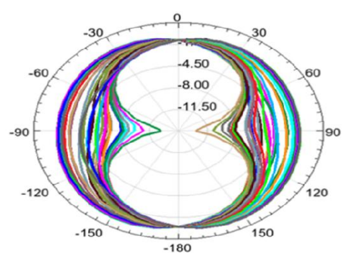

Fig 6. Frequency Response

The results demonstrate consistent impedance matching and low mutual coupling over the entire UWB range. The seamless integration of staircase-shaped monopoles and the EBG structure ensures a stable and reliable frequency response. The antenna's performance remains consistent across various frequencies, making it ideal for practical deployment in UWB communication systems.

V. CONCLUSION

In future work, the antenna design can be further optimized through experimental validation to compare measured and simulated results. Minor adjustments to the EBG structure or monopole geometry can further enhance isolation and bandwidth. Additionally, expanding the design for multi-band or reconfigurable applications can further increase its versatility in next-generation communication systems.

Overall, the proposed MIMO antenna offers a balanced solution by addressing the trilemma of compactness, wide bandwidth, and high isolation. Its superior performance, combined with ease of fabrication and cost-effectiveness, makes it a promising candidate for various ultra-wideband applications in modern wireless communication systems.The proposed antenna's applicability spans across various domains, including 6G networks.

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VI. FUTURE SCOPE

- **6G Networks:** The 9.49 GHz bandwidth supports THz-frequency backhaul links for 6G small-cell networks.
- **Wearable IoT:** Miniaturized size suits smartwatches, while omnidirectional patterns ensure connectivity during motion.
- **Autonomous Vehicles:** UWB's high-resolution radar imaging aids collision avoidance, with isolation >20 dB reducing sensor cross-talk.
- **Industrial IoT:** Low mutual coupling (−36.9 dB) prevents interference in dense M2M communication.
- **Military Systems:** UWB's low spectral density (−41.3 dBm/MHz) enables covert operations.

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