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HFSS-Based Design of Quad-Band Mimo Antenna with Isolation Enhancement using Dgs

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ABSTRACT

As wireless communication systems evolve rapidly, leading to an increasing demand for compact multi-band antennas. These designs must support services such as WLAN, WiMAX, and X-band operations simultaneously reducing system complexity and physical size. However, a significant challenge in developing such multi-channel MIMO (Multiple-Input Multiple-Output) systems is the presence of multi-path fading and the high mutual coupling between closely spaced antenna elements, both of which can severely degrade overall performance. To address these issues, this project presents a compact quad-band MIMO antenna designed on an FR4 substrate with overall dimensions of L=60mm, W=60mm, H=0.8mm. The design utilizes two horizontally placed, slotted F-shaped radiation patches fed by microstrip lines. To achieve the four required operating bands, we implemented a strategy of slotting the main patches to create a third band for the 5.25 GHz band, while the two original branches of the F-shape handle the 3.5 GHz and 7.5 GHz bands and 8-12GHz X-band. Furthermore, to overcome the challenge of mutual interference, a Defected Ground Structure (DGS) is integrated into the design, ensuring high isolation between the ports and reliable MIMO performance.

Keywords: MIMO, quad band, F-shaped antenna, Defected ground structure (DGS), Mutual coupling, isolation

INTRODUCTION

The rapid expansion of wireless communication standards has created a significant demand for compact, multi-functional antennas capable of supporting diverse services within a single hardware framework. Modern applications such as WLAN, 5G sub-6 GHz, and X-band radar require radiating structures that can operate across multiple frequency bands without increasing the physical volume of the device. To achieve high data rates and reliable signal transmission in complex environments, Multiple-Input Multiple-Output (MIMO) technology is widely implemented. However, a major challengein compact MIMO systems is the high mutual coupling between closely spaced elements, which can severely degrade diversity performance and signal integrity. This paper proposes a compact quad-band MIMO antenna designed on an FR4 substrate with dimensions of 60 mm × 60 mm × 0.8 mm. The design utilizes dual slotted F-shaped patches that are meticulously tuned to resonate at 2.45 GHz,
3.25 GHz, 5.25 GHz, and 8–12 GHz. To mitigate mutual interference, a Trapezoidal Defected Ground Structure (DGS) is integrated into the ground plane to suppress surface wave propagation. Simulation results obtained from Ansys HFSS confirm that the isolation (S21) remains below -20dB across all operational bands. Furthermore, the antenna demonstrates a low Envelope Correlation Coefficient (ECC) and stable radiation patterns, confirming its suitability for high-speed data transmission.

LITERATURE SURVEY

[1] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*, Artech House, 2001. The demand for multi-service integration has led to significant research in multi-band antennas. established the foundational theory that introducing specific slots into a microstrip patch can excite higher-order resonant modes, allowing a single radiator to cover multiple bands. Specifically, for WLAN and 5G applications, demonstrated that modifying patch geometries can successfully cover the 3.3–5.0 GHz spectrum, though achieving a consistent quad-band response including the X-band (8–12 GHz) remains a challenge in compact designs.

[2] R. K. Mistri and S. K. Mahto, "A compact quad element human face-shaped wideband MIMO antenna for 5G applications," *Int. J. Commun. Syst.*, 2024. F-shaped geometries are highly valued for their ability to provide independent control over resonant frequencies. Research showed that an F-shaped slot configuration allows for the excitation of triple resonant modes (2.4/3.5/5.8 GHz) by simply adjusting the lengths of the horizontal arms. This project builds upon this by utilizing a slotted F-shaped patch to further extend the bandwidth into the X-band, providing a unified solution for both consumer electronics and satellite communication. R. A. Pandhareetal., "Beam-steering in microstrip patch antenna array using DGS," *IEEE*, 2015. Integrating Multiple-Input Multiple-Output (MIMO) technology is essential for high data rates, but it introduces the bottleneck of mutual coupling. when antenna elements are placed in close proximity (>0.5lambda), electromagnetic interference significantly degrades diversity performance. To maintain an Envelope Correlation Coefficient (ECC) below the industry standard of 0.5, specialized decoupling structures are required to suppress these surface waves.

[3] R. K. Gupta et al., "Dual C-slotted Microstrip Patch MIMO Antenna for Multiband Wireless Applications," *Scribd*, 2017. To improve port-to-port isolation without increasing the antenna's footprint, Defected Ground Structures (DGS) are widely employed. He proved that etching defects in the ground plane acts as a band-stop filter for surface currents. Specifically, research into Trapezoidal DGS shapes has shown they provide superior suppression of mutual coupling ($S21 < -20$dB) compared to traditional rectangular or circular defects. This technique is utilized in this project to ensure high isolation on a compact 60 mm
× 30 mm footprint.

[4] A. Kumar et al., "A Compact 4-port MIMO Antenna for 5G NR and Wi-Fi 5/6/6E Applications," *ResearchGate*, 2024. Modern antenna design relies on high-fidelity simulation. Literature consistently highlights Ansys HFSS as the benchmark for electromagnetic modelling due to its accuracy in Finite Element Method (FEM) analysis. It Studied by emphasize that parametric optimization within HFSS is vital for tuning complex multi-band structures and verifying that radiation patterns remain stable across the entire quad-band operational range.

EXISTING METHOD

The multi-band resonance is often achieved by using multiple radiating patches or stacked configurations. While these methods are effective for reaching different frequencies, they significantly increase the vertical profile and overall volume of the antenna, making them unsuitable for slim, modern handheld devices. Most existing systems utilize standard rectangular or circular patches that lack the degrees of freedom required to independently tune four distinct frequency bands.

Existing MIMO designs often address mutual coupling by increasing the physical separation between the radiating elements. While this naturally reduces electromagnetic interference, it leads to a bulky antenna system that cannot be integrated into compact 5G hardware. Alternative existing methods include the use of parasitic elements or physical neutralization lines, which often increase design complexity and can negatively impact the antenna's radiation efficiency.

Most conventional microstrip antennas utilize a solid, uniform metallic ground plane. While this provides a stable reference, it allows for the free propagation of surface waves between adjacent ports in a MIMO configuration. In existing literature, antennas with uniform grounds frequently exhibit isolation levels S21 between -10dB and -15dB. This level of interference is often insufficient for high-speed data transmission, resulting in a high **Envelope Correlation Coefficient (ECC)** that limits the diversity gain of the system.

A significant portion of existing research is dedicated to optimizing antennas for a single standard, such as WLAN only or 5G only. Consequently, devices must integrate multiple separate antennas to support various services (Bluetooth, Wi-Fi, Radar,5G), leading to increased power consumption, higher manufacturing costs, and potential electromagnetic compatibility (EMC) issues within the device housing.

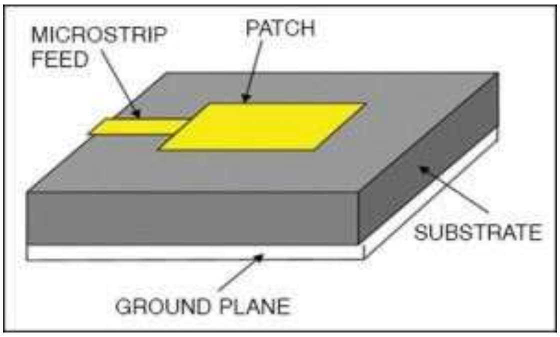

Fig1: Structure of Conventional Microstrip Patch Antenna

MICROSTRIP PATCH ANTENNA

To address the limitations of conventional single-band microstrip patch antennas, a dual-port quad-band MIMO antenna is proposed for operation across WLAN, 5G, and X-band frequencies. The selection of a slotted F-shaped geometry is intended to create multiple resonant paths, which in turn enhances the bandwidth, radiation characteristics, and impedance matching across four distinct frequency bands compared to traditional rectangular shapes.

The proposed antenna structure consists of two symmetrical F-shaped radiating patches printed on a low-profile FR4 dielectric substrate with a Trapezoidal Defected Ground Structure (DGS) on the opposite side. The substrate material (€r=4.4, h=0.8mm) is chosen to balance cost-effectiveness with high-frequency performance, and the antenna dimensions (60mm×60mm) are carefully optimized to achieve resonance at 2.45 GHz, 3.25 GHz, 5.25 GHz, and 8–12 GHz. A microstrip line feeding technique is employed due to its simplicity and ease of integration with compact planar circuits.

The antenna is designed and analyzed using Ansys High Frequency Structure Simulator (HFSS). Key design parameters, including the arm lengths of the F-shape, the dimensions of the ground defects, and the feed line positions, are optimized to obtain superior isolation and return loss. The simulation results indicate that the proposed antenna achieves a return loss (S11) better than -10dB and mutual coupling (S21) below -20dB, alongside stable radiation patterns and a low Envelope Correlation Coefficient (ECC). Thus, the proposed quad-band MIMO antenna offers enhanced isolation and a compact footprint, making it highly suitable for advanced high-frequency applications such as 5G communication, multi-standard IoT gateways, and radar technologies.

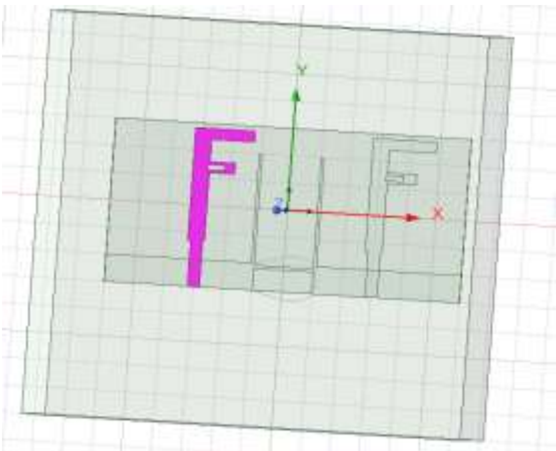

Fig:2 3D view proposed MIMO antenna

DESIGN EQUATIONS AND CALCULATIONS

The dimensions of the radiating elements on the **FR4 substrate** (er = 4.4, h = 0.8mm) are calculated using the following mathematical model.The width of the patch is calculated to ensure efficient radiation and proper impedance matching:

$$W = \frac{c}{2f_0\sqrt{\frac{\epsilon_r+1}{2}}}$$

As the electromagnetic waves travel through both the substrate and air, the effective dielectric constant must be determined:

$$\epsilon_{reff} = \frac{\epsilon_r+1}{2} + \frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2}$$

Due to fringing fields at the edges of the patch, the electrical length is slightly greater than the physical length. This extension is calculated as:

$$\Delta L = 0.412h\frac{(\epsilon_{reff}+0.3)(\frac{W}{h}+0.264)}{(\epsilon_{reff}-0.258)(\frac{W}{h}+0.8)}$$

The physical length of the resonating element is then determined by:

$$L = \frac{c}{2f_0\sqrt{\epsilon_{reff}}} - 2\Delta L$$

By applying these equations, the initial geometry was drafted, and the Trapezoidal DGS was then numerically optimized to suppress the surface waves that occur at these calculated resonant frequencies.

RESULTS AND DISCUSSION

The performance of the proposed quad-band MIMO antenna has been investigated and validated using Ansys HFSS software. The antenna structure provides a return loss (S11) significantly less than -10dB and a VSWR of less than 2 across all four operating frequency bands: 2.45 GHz, 3.25 GHz, 5.25 GHz, and 8–12 GHz. Due to the integration of a Trapezoidal Defected Ground Structure (DGS), the design achieves high port-to-port isolation (S21) of less than -20dB and a low Envelope Correlation Coefficient (ECC). The design also exhibits improved gain and stable radiation characteristics across the spectrum, making it highly suitable for multi-service applications such as WLAN, 5G communication, and X-band radar systems.

Fig:3 Input Port and Power Configuration in HFSS

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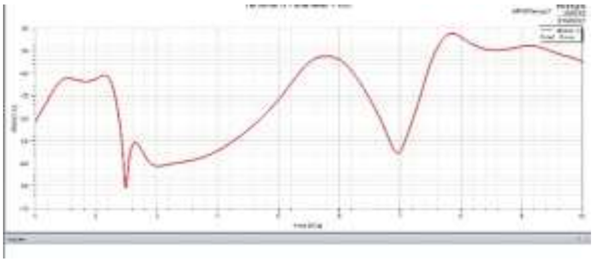

Fig:4 Reflection coefficient analysis

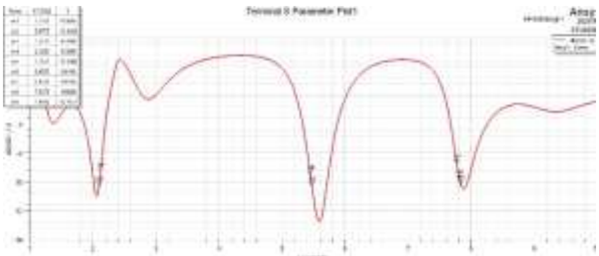

Fig:5 Return loss analysis

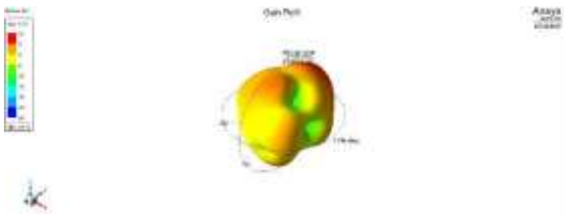

Fig:6 Gain

Fig:7 Radiation Pattern

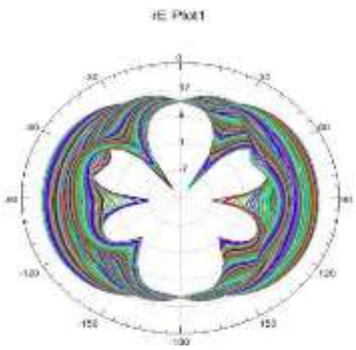

Fig:8 VSWR

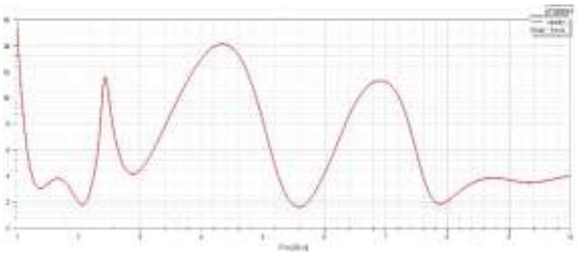

Table 1: Results Summary

Parameters	**Target**	**Obtained**
Resonant frequency	8-12GHz	~8-12GHz
Return loss(S11)	-10dB	-13dB
Reflection coefficient(S21)	-20dB	>-20dB
Gain	5.3	5.33
VSWR	<2	1.8

CONCLUSION

In this work successfully presented the design and analysis of a compact quad-band MIMO antenna system for modern wireless applications. By utilizing dual slotted F-shaped radiating elements on a cost-effective FR4 substrate, the antenna achieved stable resonance at 2.45 GHz, 3.25 GHz, 5.25 GHz, and the X-band (8–12 GHz). The integration of a Trapezoidal Defected Ground Structure (DGS) proved highly effective in mitigating mutual coupling, maintaining port-to-port isolation (S21) below -20dBacross all operational bands. Simulation results obtained from Ansys HFSS validated the antenna's high performance, showing a return loss (S11) of less than -10dB and a Voltage Standing Wave Ratio (VSWR) of less than 2. The compact footprint of 60mm×60mm and its multi-band capability make this antenna an ideal solution for space-constrained IoT gateways, 5G communication devices, and radar sensing systems. Future work could involve the fabrication of the prototype and experimental validation of the radiation patterns in an anechoic chamber to further confirm the simulation results.

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[3] H. Wang et al., "Novel F-shaped quad band printed slot antenna for WLAN and WiMAX MIMO systems," *ResearchGate*, 2022.

[4] R. A. Pandhare et al., "Beam-steering in microstrip patch antenna array using DGS," *IEEE*, 2015.

[5]R. K. Gupta et al., "Dual C-slotted Microstrip Patch MIMO Antenna forMultiband Wireless Applications," *Scribd*, 2017.Multiband Wireless Applications," *Scribd*, 2017.

[6] A. Kumar et al., "A Compact 4-port MIMO Antenna for 5G NR and Wi-Fi 5/6/6E Applications," *ResearchGate*, 2024.