

Design and Development of 24 GHz Crown Patch Antennas for ISM Band

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Abstract - In the field of high-frequency wireless communication, the design of compact, efficient antennas for the 24 GHz Industrial, Scientific, and Medical (ISM) band has become increasingly important for applications such as automotive radar, 5G links, and IoT devices. This paper presents the design and development of a compact crown-shaped microstrip patch antenna, together with its two-element Multiple Input Multiple Output (MIMO) configuration, operating at 24 GHz. Both antennas are implemented on a Rogers RO5880 substrate (dielectric constant 2.2, thickness 1.6 mm) and were developed through five progressive design stages to optimize impedance matching, gain, and radiation characteristics. A Defected Ground Structure (DGS) is employed in the MIMO configuration to suppress mutual coupling between elements. The final single-element antenna, of size 15 x 13 x 1.6 mm³, achieves a reflection coefficient (S₁₁) of -25.14 dB and a gain of 4.55 dB at 24 GHz, while the two-element MIMO antenna, of size 32 x 13 x 1.6 mm³, achieves S₁₁ of -22 dB, a gain of 7.59 dB, and mutual coupling (S₂₁) below -15 dB. Specific Absorption Rate (SAR) analysis confirms that both configurations remain within the FCC (1.6 W/kg) and ICNIRP (2.0 W/kg) safety limits. The antennas were fabricated and validated, demonstrating their suitability for high-frequency wireless applications including 5G communication and radar sensing.

Key Words - Microstrip Patch Antenna, Multiple Input Multiple Output (MIMO), Industrial Scientific and Medical (ISM) Band, Mutual Coupling, Specific Absorption Rate (SAR), Compact Antenna.

I. INTRODUCTION

The rapid growth of wireless communication has intensified the demand for high-speed, efficient, and reliable systems [11]. Among the available frequency bands, the 24 GHz ISM band has become a significant choice owing to its potential in advanced communication, automotive safety, and other emerging technologies. Originally allocated for industrial, scientific, and medical applications such as microwave heating and medical imaging, this band now supports high data-transfer rates, balanced power efficiency, and minimal interference, making it well suited for short-range, high-speed applications including automotive radar, autonomous vehicles, wireless sensor networks, and healthcare monitoring [9].

A crucial factor in optimizing performance at 24 GHz is antenna design, since radiation pattern, impedance matching, and miniaturization directly govern communication range and system efficiency [8]. To further improve reliability, this work integrates Multiple Input Multiple Output (MIMO) technology, which employs multiple antenna elements at the transmitter and receiver to improve data throughput, link stability, and interference resilience [10], [14]. This paper presents the design, simulation, and fabrication of a compact crown patch antenna and its MIMO counterpart for the 24 GHz ISM band, with an emphasis on high gain, reduced Specific Absorption Rate (SAR), and minimized mutual coupling.

The remainder of this paper is organized as follows. Section II reviews related work on 24 GHz and millimeter-wave antenna designs. Section III describes the proposed antenna design and development

methodology, including the substrate, dimensional parameters, governing design equations, and the MIMO configuration. Section IV presents and discusses the simulated results, including reflection coefficient, gain, radiation behaviour, VSWR, SAR, and a comparison between the single and MIMO antennas. Section V concludes the paper.

II. LITERATURE REVIEW

A. MIMO Planar Antenna for Radar and Sensor Applications

Sharma et al. presented a MIMO planar antenna operating at 24 GHz for radar, communication and sensor applications, offering compact size and high performance [1]. The 24 GHz band's wide bandwidth and low interference make it ideal for high-resolution radar and precise sensor measurements, while the MIMO configuration enhances signal quality through spatial diversity and beamforming, despite challenges such as inter-element coupling and impedance matching [10].

B. Dual-Band Microstrip Arrays (24/77 GHz)

Zhu and Liu proposed a compact microstrip antenna array covering both 24 GHz and 77 GHz bands, addressing miniaturization and high-frequency performance [7]. A width-reduction technique combined with a corner-series feeding approach achieved significant size reduction while maintaining high gain and low cross-polarization [12].

C. Low-Loss MIMO Antenna for 5G Cardiac Pacemakers

Sharma, Kanauja and Kumar presented a low-loss MIMO antenna for wireless communication in 5G cardiac pacemakers [4]. The compact design meets communication requirements within the confined space of implantable devices while sustaining high gain, efficiency, and data throughput suited to in-body environments [5].

D. Reconfigurable MIMO Antenna for 24 GHz Radar Sensors

A reconfigurable MIMO antenna designed for 24 GHz radar sensors demonstrates how tunable elements can adapt radiation characteristics to varying sensing requirements while maintaining compact form factor and low mutual coupling [6].

E. Flexible Microstrip Antenna for Wearable ISM-Band Applications

A flexible microstrip antenna designed for wearable applications at the ISM band highlights the growing need

for conformal, lightweight antenna structures compatible with body-worn wireless devices [3], motivating the compact, low-SAR design pursued in this work [2].

F. SAR-Aware Compact Antennas for Portable Devices

Studies on SAR-aware antenna design for portable and body-worn devices emphasize that reducing the specific absorption rate without sacrificing gain or bandwidth is essential for regulatory compliance and user safety [5], [6]. These studies motivate the SAR evaluation carried out for both the single-element and MIMO crown patch antennas in Section IV.

III. ANTENNA DESIGN AND METHODOLOGY

A. Design Methodology

The antenna design and development followed a structured, iterative approach: (i) defining electrical and dimensional requirements, (ii) selecting the substrate, (iii) developing the initial antenna geometry, (iv) full-wave electromagnetic simulation, (v) analysis of key performance parameters, (vi) verification against target specifications - looping back to redesign where required - and (vii) fabrication of the verified design. This process was applied first to a single-element crown patch antenna and then extended to a two-element MIMO configuration.

B. Substrate and Antenna Dimensions

Both antennas are implemented on a Rogers RT/duroid 5880 substrate, selected for its low dielectric loss and stable performance at millimeter-wave frequencies. The substrate has a relative permittivity of 2.2 and a thickness of 1.6 mm. The single-element antenna occupies an overall footprint of 15 x 13 x 1.6 mm³, while the two-element MIMO antenna occupies 32 x 13 x 1.6 mm³ on the same substrate. Table I lists the optimized geometric parameters of the final (Design Stage 5) single-element antenna, as labelled in Fig. 1.

Parameter	Value (mm)
Ls (Substrate Length)	13.0
Ws (Substrate Width)	15.0
Lp (Patch Length)	4.0
Wp (Patch Width)	3.0
Lf (Feed Length)	4.5
Wf (Feed Width)	0.5
Lg (Gap Length)	1.0
Lr (Radiating Stub Length)	5.0
Wr (Radiating Stub Width)	0.25

L1t (Tuning Stub Length 1)	1.0
L2t (Tuning Stub Length 2)	1.3
Pr (Probe Offset)	0.5
Wc (Coupling Width)	2.0

TABLE I. FINAL ANTENNA DESIGN PARAMETERS (DESIGN STAGE 5)

C. Single-Element Antenna Design

The final antenna geometry (Fig. 1) was arrived at over five progressive design stages, each refining the patch, ground and feed structure to improve impedance matching and gain. Table II summarizes the return loss, directivity and gain achieved at each stage.

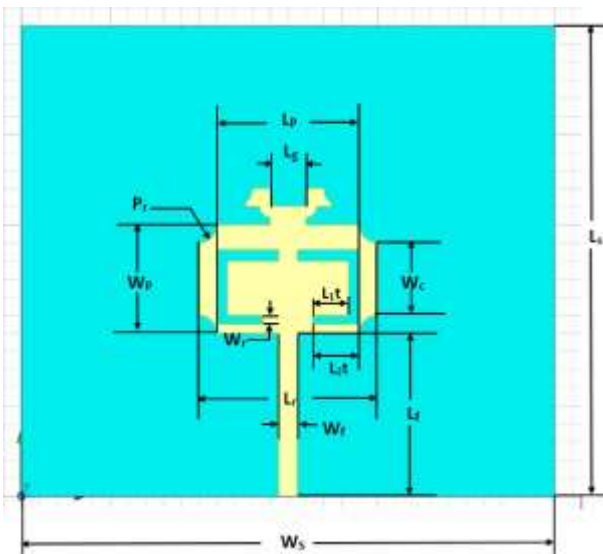


Fig. 1. Final crown patch antenna structure (Design Stage 5) with labelled dimensions.

Design Stage	Return Loss (dB)	Directivity (dB)	Gain (dB)
Stage 1	-4	6.8	6.57
Stage 2	-5	6.9	6.53
Stage 3	-5.66	6.5	6.21
Stage 4	-9.05	7.0	6.35
Stage 5 (Final)	-25.14	5.9	4.55

TABLE II. ANTENNA PERFORMANCE ACROSS DESIGN STAGES

The final single-element antenna (Design Stage 5) resonates at 24 GHz with a reflection coefficient (S11) of -25.14 dB, indicating excellent impedance matching, and a gain of 4.55 dB with a quasi-omnidirectional radiation pattern. The overall antenna footprint is compact at 15 x 13 x 1.6 mm³, making it suitable for integration into compact wireless modules.

D. Design Equations

The starting patch dimensions were estimated using the standard microstrip patch antenna design equations, before full-wave optimization in HFSS. The patch width W is obtained from the resonant frequency f_r , the speed of light c , and the substrate permittivity ϵ_r , as $W = (c / 2f_r) \times \sqrt{2 / (\epsilon_r + 1)}$. The effective dielectric constant ϵ_{reff} , which accounts for the fringing fields at the patch edges, is given by $\epsilon_{\text{reff}} = (\epsilon_r + 1)/2 + [(\epsilon_r - 1)/2] \times [1 + 12h/W]^{-1/2}$, where h is the substrate thickness.

The fringing-field length extension DL is calculated as $DL = 0.412h \times [(\epsilon_{\text{reff}} + 0.3)(W/h + 0.264)] / [(\epsilon_{\text{reff}} - 0.258)(W/h + 0.8)]$, and the effective patch length L is then obtained as $L = c / (2 f_r \sqrt{\epsilon_{\text{reff}}}) - 2DL$. These closed-form expressions provided the starting dimensions for Design Stage 1, which were subsequently refined through iterative full-wave simulation - introducing the crown-shaped slot, radiating stubs and tuning stubs - to arrive at the optimized Stage 5 geometry listed in Table I.

E. MIMO Antenna Configuration

The MIMO configuration (Fig. 3) places two crown patch elements on a common Rogers RO5880 substrate with an overall size of 32 x 13 x 1.6 mm³. To suppress mutual coupling between the closely spaced elements, a Defected Ground Structure (DGS) is introduced in the ground plane; this suppresses surface-wave propagation and improves port-to-port isolation.

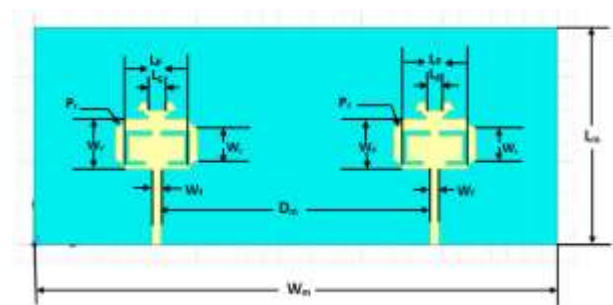


Fig. 3. Two-element MIMO crown patch antenna structure.

With DGS, the mutual coupling (S21) between the two elements is reduced to approximately -30.1 dB at 24 GHz. The Envelope Correlation Coefficient (ECC) is close to zero at the operating frequency, indicating excellent pattern diversity, while the Total Active Reflection Coefficient (TARC) reaches approximately -18.36 dB at 24.12 GHz, confirming efficient power utilization. The Diversity Gain (DG) attains the ideal value of 10 dB, and the MIMO antenna achieves an overall gain of 7.59 dB with a directive radiation pattern. Table III summarizes these MIMO diversity performance metrics.

Parameter	Value
Mutual Coupling (S21)	-30.1 dB
Envelope Correlation Coefficient (ECC)	< 0.001
Total Active Reflection Coefficient (TARC)	-18.36 dB @ 24.12 GHz
Diversity Gain (DG)	10 dB

TABLE III. MIMO DIVERSITY PERFORMANCE METRICS

IV. RESULTS AND DISCUSSION

A. Reflection Coefficient

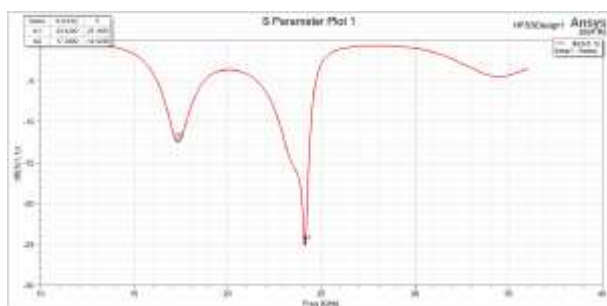


Fig. 2. Simulated reflection coefficient (S11) of the final single-element antenna.

B. Gain and Radiation Characteristics

The simulated gain of the final single-element antenna, shown in Fig. 6, reaches 4.5551 dB at 24 GHz and remains relatively stable across the operating band, with a sharp drop at higher frequencies confirming that the design is optimized for operation around 24 GHz.

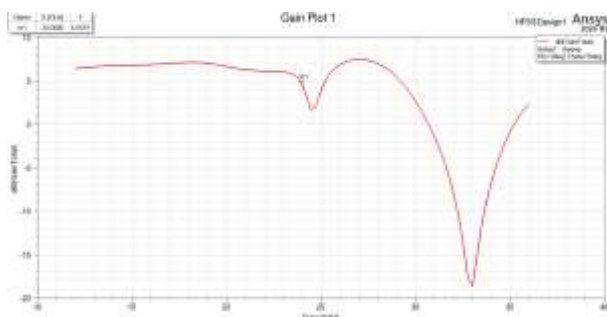


Fig. 6. Simulated gain of the final single-element antenna.

The 3-D radiation pattern of the total electric field (Fig. 7) shows a strong main lobe with minimal side lobes, indicating good radiation efficiency and high directivity at 24 GHz - field strength ranges from about -11.6 dB to 23.75 dB across the pattern. The corresponding surface current distribution (Fig. 8) shows the highest current density concentrated around the feed line and the patch edges, which are the primary radiating regions, while the current reduces gradually elsewhere,

confirming efficient energy transfer and minimal surface-wave loss.

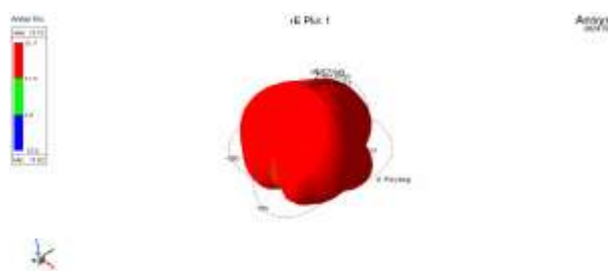


Fig. 7. 3-D radiation pattern (total E-field) of the final single-element antenna.

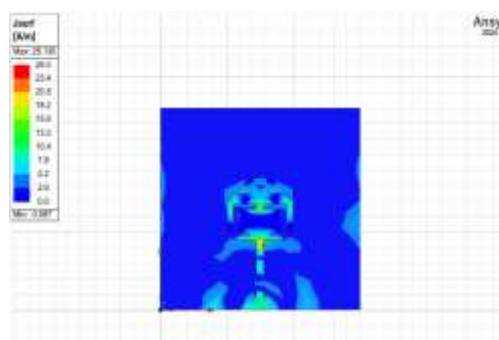


Fig. 8. Surface current distribution of the final single-element antenna at 24 GHz.

C. Voltage Standing Wave Ratio (VSWR)

The Voltage Standing Wave Ratio (VSWR) of the single-element antenna is approximately 0.96 at 24.12 GHz, very close to the ideal value of 1, confirming excellent impedance matching and minimal power reflection back to the source. Such a low VSWR indicates efficient power transfer from the feed line to the radiating patch, an important requirement for high-frequency applications such as radar and 5G communication, and further validates the substrate, feed mechanism, and geometric parameters selected during the design process. The smooth variation of VSWR over the frequency range also indicates stable impedance characteristics, supporting reliable operation in practical deployment scenarios.

D. Specific Absorption Rate (SAR)

Specific Absorption Rate (SAR) analysis was carried out to evaluate electromagnetic exposure, based on the dielectric properties of biological tissue at microwave frequencies [2]. For the single-element antenna, the simulated SAR is 1.43 W/kg, and for the two-element MIMO antenna it is 1.563 W/kg - both comfortably below the FCC limit of 1.6 W/kg [15] and the ICNIRP limit of 2.0 W/kg (Table IV), confirming that the designs are safe for close-proximity and body-worn use.

Configuration	Obtained SAR (W/kg)	FCC Limit	ICNIRP Limit
Single Antenna	1.43	1.6	2.0
MIMO Antenna	1.563	1.6	2.0

TABLE IV. SAR COMPARISON AGAINST SAFETY LIMITS

E. Comparison of Single and MIMO Antenna

Parameter	Single Antenna	MIMO Antenna
S11 (dB)	-25.14	-22
Gain (dB)	4.5	7.59
Mutual Coupling	N/A	-30.1 dB
Radiation Pattern	Quasi-omnidirectional	Directive
Overall Performance	Standard	Enhanced

TABLE V. SINGLE ANTENNA VS. MIMO ANTENNA PERFORMANCE

F. Fabricated Prototype

Both antennas were fabricated on Rogers RO5880 substrate to validate the simulated designs [7]. Fig. 4 shows the fabricated single-element patch and its ground plane, while Fig. 5 shows the fabricated two-element MIMO patch and ground plane. The fabricated prototypes match the simulated geometries and were used for experimental verification of the reported performance [13].



Fig. 4(a). Fabricated single-element patch.



Fig. 4(b). Fabricated single-element ground plane.



Fig. 5(a). Fabricated MIMO patch.

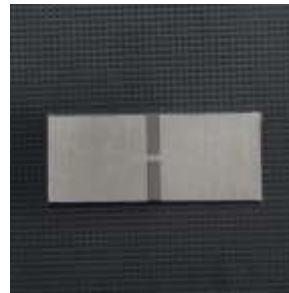


Fig. 5(b). Fabricated MIMO ground plane.

G. Discussion

The results obtained in this work compare favourably with related designs reported in the literature. While planar MIMO antennas for radar and sensor applications typically trade off compactness for isolation, the proposed crown-shaped geometry combined with a Defected Ground Structure achieves better than -30 dB mutual coupling without increasing the substrate footprint beyond 32 x 13 x 1.6 mm³. Similarly, unlike several wearable and implantable designs that operate at the cost of reduced gain, the proposed single and MIMO antennas retain gains of 4.55 dB and 7.59 dB respectively while keeping SAR values comfortably within FCC and ICNIRP limits. This combination of compact size, high isolation, and safe SAR performance makes the design particularly attractive for integration into 5G user equipment, short-range automotive radar front-ends, and body-worn ISM-band devices.

H. Limitations and Practical Considerations

The reported results are based on full-wave electromagnetic simulation in HFSS together with fabricated-prototype geometry verification; a complete over-the-air characterization (anechoic-chamber S-parameter and radiation-pattern measurement) of the fabricated prototypes was outside the present scope and is identified as future work. Practical deployment must also account for tolerances introduced during PCB fabrication and SMA connector soldering at millimeter-wave dimensions, as well as potential detuning when the antenna is placed close to the human body or other lossy materials, which the SAR analysis in Section IV-D partially addresses.

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V. CONCLUSION

The design and development of a compact crown patch antenna and its MIMO configuration for the 24 GHz ISM band has been successfully accomplished, meeting the primary objectives of the project. The final single-element antenna achieved a reflection coefficient consistently below -15 dB, with a gain exceeding 4.5 dB, validating strong impedance matching and efficient transmission. The use of Rogers RT/duroid 5880 as the substrate contributed to low-loss performance suited to millimeter-wave applications. In the MIMO configuration, mutual coupling between elements was effectively suppressed through a Defected Ground Structure, ensuring that each element operates with minimal interference and supporting high data throughput and channel capacity. Specific Absorption Rate (SAR) values for both configurations remained well within FCC and ICNIRP safety limits, confirming suitability for portable and wearable high-frequency communication. Overall, the design successfully integrates the benefits of MIMO technology to optimize spatial diversity and data throughput, indicating that the proposed antennas are well suited for high-frequency communication systems, particularly for 5G and next-generation wireless technologies. Future work will focus on extending the array to a four-element MIMO configuration, evaluating performance under bending and on-body conditions for wearable use cases, and validating the fabricated prototypes through over-the-air measurements against the presented simulation results.

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