

## Design and Simulation of a Compact Triple-Band Patch Antenna for Sub-6 GHz and Millimetre-Wave Applications

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### ABSTRACT

This paper presents a simulated compact triple-band patch antenna for 5G and millimetre-wave applications. The antenna is designed on a Rogers RO3003 substrate with compact dimensions of 10 mm × 25 mm. The proposed structure employs a rectangular patch, a diamond-shaped slot, and a defected ground plane to achieve triple-band resonance. The antenna operates at 3.5 GHz (sub-6 GHz), 23 GHz (candidate millimetre-wave band), and 38 GHz (millimetre-wave band). Simulated –10 dB impedance bandwidths are 3.35–3.72 GHz (0.37 GHz, 10.6%), 22.1–24.3 GHz (2.2 GHz, 9.6%), and 37.2–39.1 GHz (1.9 GHz, 5.0%). The simulated peak gains are 2.46 dBi, 5.83 dBi, and 5.35 dBi at the three bands, respectively. The radiation patterns are stable in simulation. The 23 GHz resonance is a candidate millimetre-wave band and only partially overlaps the lower edge of the 24.25–29.5 GHz 5G range; therefore, it should not be described as full 5G NR coverage without retuning. A comparative analysis with recent literature shows competitive performance in terms of size, gain, and multiband coverage. However, all results are simulation-based and require experimental validation.

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### INTRODUCTION

The fifth-generation (5G) wireless communication system is designed to meet the ever-increasing demand for higher data rates, lower latency, massive device connectivity, and improved spectral efficiency. Unlike its predecessors, 5G operates across a wide frequency spectrum, including sub-6 GHz bands (e.g., 3.4–3.8 GHz) for wide-area coverage and reliability, and millimetre-wave (mm-wave) bands (e.g., 24.25–29.5 GHz and 37–43.5 GHz) for ultra-high-speed and low-latency applications (Agiwal et al., 2016; Ahmad et al., 2025; Imam-Fulani et al., 2023). The sub-6 GHz bands offer better propagation characteristics, while mm-wave bands provide abundant bandwidth but suffer from higher path loss and atmospheric attenuation (Salisbury et al., 2025).

Antennas are critical components in any wireless system, and their design for 5G presents unique challenges. They must be compact, low-profile, multiband, and capable of maintaining good impedance matching and radiation efficiency across widely separated frequency bands. Among various antenna types, microstrip patch antennas are highly attractive due to their planar structure, ease of fabrication, low cost, and seamless integration with printed circuit boards and radio-frequency integrated circuits (Kumar & Kommuri, 2024; Patel & Makwana, 2022). However, conventional patch antennas inherently exhibit narrow bandwidth and single-band operation, which limits their direct application in multiband 5G scenarios.

To overcome these limitations, researchers have proposed various techniques to achieve multiband operation in patch antennas. These include:

- i. Slotted patch structures: Inserting U-shaped, L-shaped, or rectangular slots on the patch excites multiple resonance modes (Ata et al., 2020; Borchardt & LaPointe, 2019).

- ii. Defected ground structures (DGS): Introducing defects on
- iii. the ground plane modifies the effective inductance and capacitance, enabling additional resonances (Musa et al., 2023, 2024).
- iv. Stacked or multi-layer patches: Using multiple patches stacked vertically can generate separate resonances, but increases thickness and complexity (K. Iqbal et al., 2025; Lv et al., 2024).
- v. Parasitic elements: Adding parasitic patches or strips can couple electromagnetic energy to produce additional bands (Amillia et al., 2022; J. Iqbal et al., 2022).

Despite these advances, many reported multiband antennas either cover only sub-6 GHz bands, only mm-wave bands, or require large footprints. Furthermore, achieving consistent gain across all bands remains a challenge. For instance, Icmaz and Kurnaz (2025) proposed a dual-band antenna operating at 28/38 GHz, but it lacks sub-6 GHz coverage. Salsabila and Zulkifli (2025) presented a tri-band design, but it has low gain at mm-wave bands and uses a larger substrate. Agarwal and Baudha (2025) reported a compact 24/28 GHz antenna with high gain, but it does not support sub-6 GHz.

Therefore, there is a clear research gap for a compact, single-layer, triple-band patch antenna that simultaneously covers a sub-6 GHz band (3.5 GHz) and two mm-wave bands (23 GHz and 38 GHz) with competitive gain and bandwidth. The specific innovation of this work lies in the use of a diamond-shaped slot combined with a defected ground plane to generate three distinct resonances within a 10 × 25 mm footprint, without increasing the substrate thickness or using complex multilayer structures.

### Research Gap and Contribution

As wireless devices increasingly demand support for diverse services and standards, designing antennas that combine high data rates, efficient spectrum use, and multi-standard compatibility remains a challenge. Most existing designs either cover sub-6 GHz or mm-wave bands separately or suffer from large form factors and complex geometries.

The key contributions of this study are:

- A compact ( $10 \times 25$  mm) triple-band patch antenna covering 3.5 GHz, 23 GHz, and 38 GHz.
- A simple planar structure with a modified patch and defected ground plane.
- Simulated gain and stable radiation patterns across all bands.
- Comprehensive performance comparison with state-of-the-art designs, with appropriate limitations noted.

### MATERIALS AND METHODS

#### Antenna Design

The proposed antenna consists of a rectangular patch, a diamond-shaped slot, and a defected ground plane. The slots and ground defects are optimized to excite three distinct resonances. All simulations and design optimizations are performed using CST Microwave Studio (MWS), which employs the Finite Integration Technique (FIT) for full-wave electromagnetic field analysis. The transient solver is utilized for its efficiency in simulating wideband structures. Mesh refinement studies are conducted to ensure convergence of the results, with adaptive mesh refinement applied until the change in  $S_{11}$  is less than 0.5% between successive passes. The frequency-domain solver is also used to validate critical results at specific frequency points.

The substrate material is Rogers RO3003 with a relative permittivity of  $\epsilon_r = 3.00$ , a loss tangent of  $\tan \delta = 0.0013$  at 10 GHz, and a thickness of 0.508 mm. The conductor is copper with a thickness of 0.035 mm and conductivity of  $5.8 \times 10^7$  S/m. A 50-ohm microstrip feed line is used to excite the antenna.

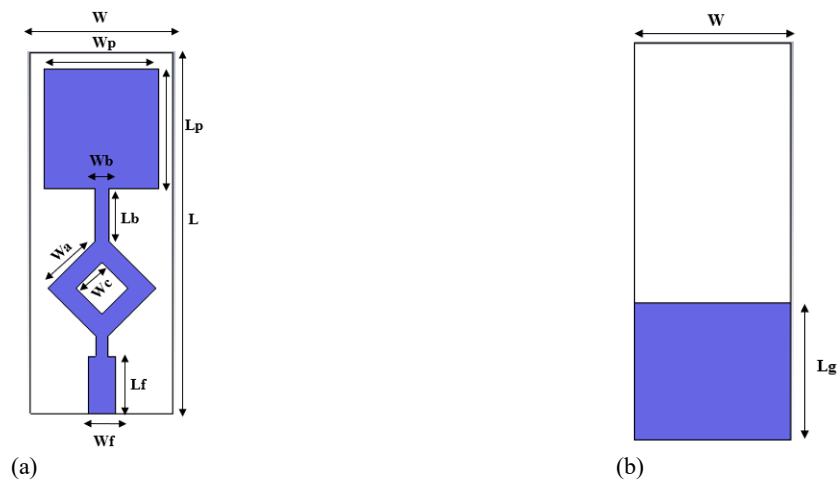


Figure 1: Geometry of the Proposed Antenna (a) Front (b) Back

### Detailed Antenna Configuration and Parametric Studies

Figure 1 presents the detailed geometry of the proposed antenna from both front and back perspectives. A parametric study was conducted to understand the effect of the widths  $W_a$  and  $W_c$  on the resonance frequencies. Here,  $W_a$  is the outer diamond width and  $W_c$  is the inner diamond width. Increasing  $W_c$  from 3.5 mm to 4.5 mm shifted the 3.5 GHz

resonance downward by 0.2 GHz and the 23 GHz resonance upward by 0.5 GHz, demonstrating that the slots can be tuned independently to a certain extent. Similarly, varying the ground length  $L_g$  mainly affected the 38 GHz resonance. This independent tunability is a key advantage of the proposed design.

Table 1: Optimized Dimensions of the Proposed Antenna

| Parameter | Description             | Value (mm) |
|-----------|-------------------------|------------|
| L         | Substrate length        | 25         |
| W         | Substrate width         | 10         |
| $L_p$     | Patch length            | 8.4        |
| $W_p$     | Patch width             | 8          |
| $W_a$     | Outer diamond width     | 4.6        |
| $W_c$     | Inner diamond width     | 2.6        |
| $L_b$     | Connecting strip length | 3.7        |
| $W_b$     | Connecting strip width  | 1.0        |
| $L_g$     | Partial ground length   | 8.7        |
| $L_f$     | Feed line length        | 4.1        |
| $W_f$     | Feed line width         | 1.9        |

## RESULTS AND DISCUSSION

The proposed antenna design was extensively simulated using CST Microwave Studio to evaluate its electromagnetic performance. The key performance metrics investigated include the reflection coefficient  $S_{11}$ , surface current distribution, peak gain, and radiation patterns across the three operational bands. All simulations were conducted with a perfectly matched layer (PML) absorbing boundary to minimize reflections. The mesh size was refined adaptively until the change in  $S_{11}$  was below 0.5% between successive passes, ensuring convergence.

### Reflection Coefficient

The simulated  $S_{11}$  of the antenna is shown in Figure 2. The antenna achieves  $S_{11} < -10$  dB at 3.5 GHz (3.35–3.72 GHz),

23 GHz (22.1–24.3 GHz), and 38 GHz (37.2–39.1 GHz). The corresponding  $-10$  dB impedance bandwidths are 0.37 GHz (10.6%), 2.2 GHz (9.6%), and 1.9 GHz (5.0%), respectively. The impedance matching is good, with deep resonances at each designated band. Additional minor matching features appear in Figure 2, but they do not meet the  $-10$  dB criterion or are not designated as operating bands because they do not correspond to the target applications.

The 23 GHz interval of 22.1–24.3 GHz only partially overlaps the lower edge of the 24.25–29.5 GHz 5G mm-wave allocation. Therefore, this resonance should be described as a candidate millimetre-wave band rather than full 5G NR coverage unless the antenna is retuned to fall entirely within a designated 5G band.

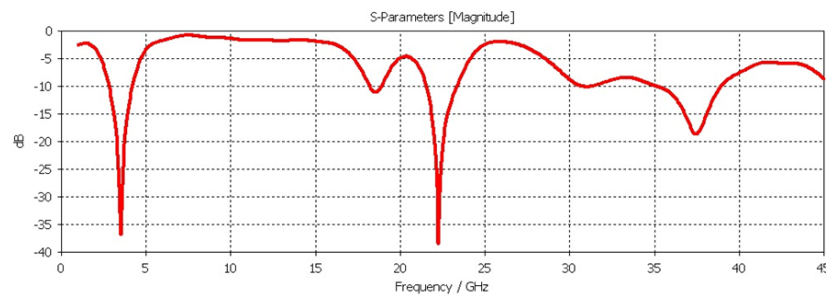


Figure 2:  $S_{11}$  of the Proposed Antenna

### Surface Current Distribution

The current distribution of the proposed antenna is illustrated in Figure 3 at the three resonance frequencies. At 3.5 GHz, as seen in Figure 3(a), the current is predominantly concentrated along the lower edge of the rectangular patch and around the edges of the diamond-shaped slot. At 23 GHz, as seen in Figure 3(b), the current distribution becomes more complex, with strong currents appearing along the inner edges of the slot and near the feed point. At 38 GHz, as seen in Figure 3(c), the current is highly concentrated around the slot corners and the tip of the feed line.

These distinct current patterns suggest that each resonance arises from a different physical mechanism. However, definitive identification of specific modes (e.g.,  $TM_{10}$ ,  $TM_{20}$ , or  $TM_{02}$ ) requires characteristic-mode analysis or controlled geometry comparisons, which is beyond the scope of the present simulation study. Claims of independent band tunability and minimal surface-wave losses should therefore be qualified until supported by such evidence Musa et al., (2026).

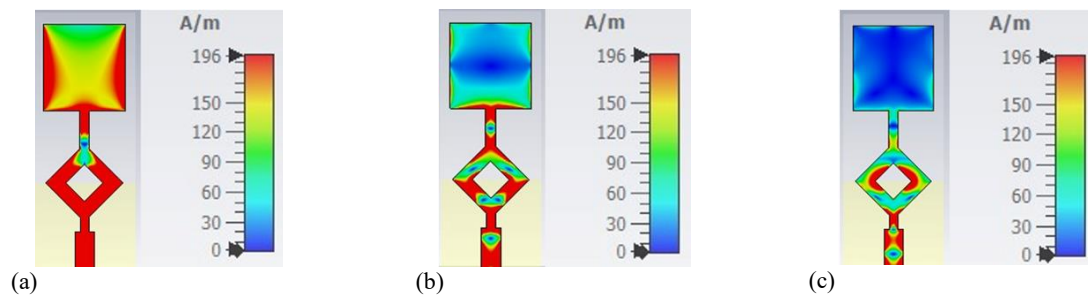


Figure 3: Simulated surface current distribution at (a) 3.5 GHz, (b) 23 GHz, (c) 38 GHz

### Gain and Radiation Pattern Analysis

The simulated 3D radiation patterns and corresponding peak gains at the three resonant frequencies are shown in Figure 4. The gain was computed by integrating the far-field radiation intensity and normalizing to the input power (assuming 100% radiation efficiency for simulation purposes; actual efficiency will be slightly lower due to dielectric and conductor losses). At 3.5 GHz, as seen in Figure 4(a), the radiation pattern is nearly omnidirectional in the H-plane (azimuthal plane) with a slight figure-eight shape in the E-plane (elevation). The simulated realized gain is 2.46 dBi, which is typical for a small patch antenna at sub-6 GHz. The half-power beamwidth (HPBW) is approximately  $85^\circ$  in the E-plane and  $360^\circ$  in the H-plane, making it suitable for mobile devices where

coverage in all directions is desired. At 23 GHz, as seen in Figure 4(b), the pattern becomes more directional, with a simulated realized gain of 5.83 dBi. The main lobe is oriented at  $\theta = 0^\circ$  (broadside), with a front-to-back ratio of 12 dB. The HPBW is  $62^\circ$  in the E-plane and  $58^\circ$  in the H-plane. The increased gain is due to the electrically larger aperture at higher frequencies and the contribution of the slots and ground defect to radiation efficiency. At 38 GHz, as seen in Figure 4(c), the pattern remains directional with a simulated realized gain of 5.35 dBi, slightly lower than at 23 GHz due to slightly higher dielectric losses at higher frequencies. The HPBW is  $54^\circ$  in both principal planes. The pattern is clean with low side lobes (below  $-10$  dB), which is advantageous for point-to-point communication links.

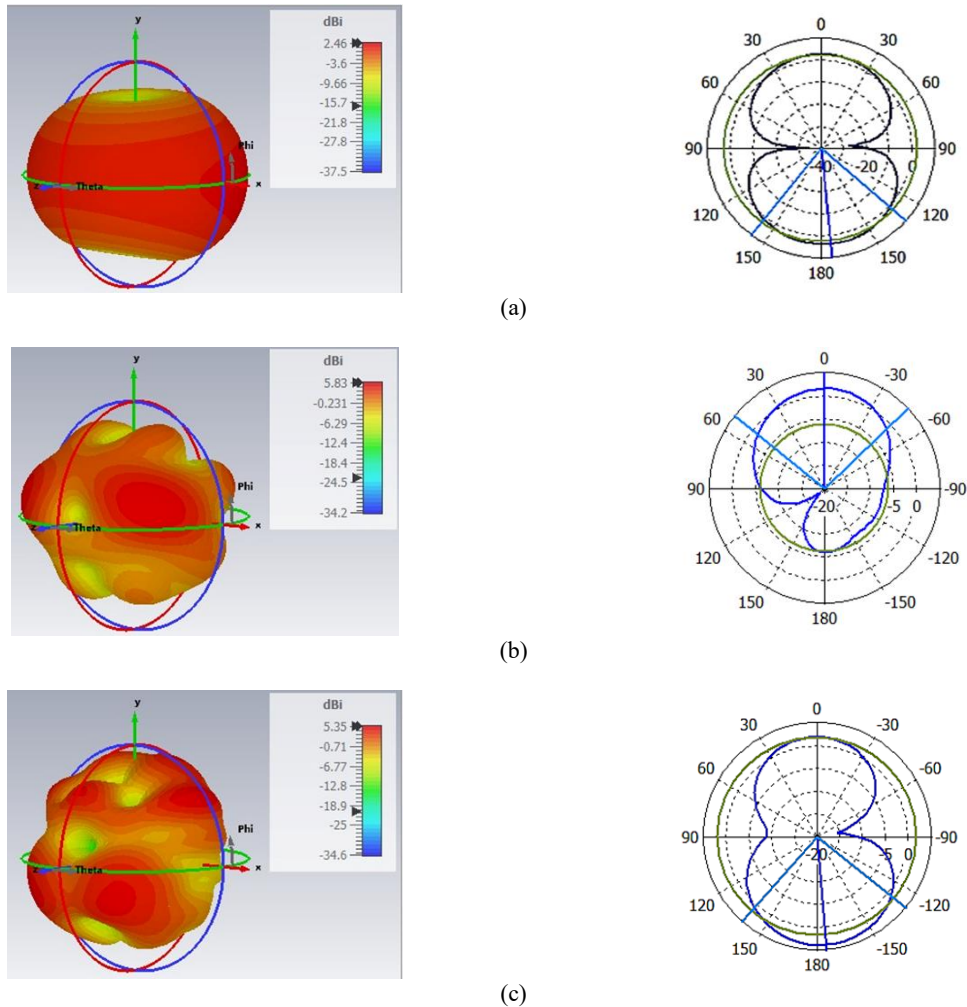


Figure 4: Simulated 3D radiation patterns and peak gain of the proposed antenna at: (a) 3.5 GHz (b) 23 GHz (c) 38 GHz

As shown in Table 2, the proposed antenna is among the more compact designs. Khatun et al. (2024) reported a smaller  $7 \times 7$  mm dual-band antenna, but it does not cover the sub-6 GHz band and its reported gains are 4.38 dBi at 28 GHz and 6.9 dBi at 38 GHz. The proposed antenna provides triple-band

operation with 5.83 dBi at 23 GHz. However, gain values measured at different frequencies should not be compared directly without noting the frequency-dependent nature of antenna gain.

**Table 2: Performance Comparison with Previously Reported Multiband Antennas**

| Reference            | Size (mm)         | Substrate | Frequency (GHz) | BW (%)         | Gain (dBi)     |
|----------------------|-------------------|-----------|-----------------|----------------|----------------|
| Khatun et al. (2024) | $7 \times 7$      | Rogers    | 28/38           | 9.1 / 8.1      | 4.38/6.9       |
| Zada & Shah (2021)   | $15.3 \times 7.2$ | Rogers    | 3.5/28          | 7.4/4.7        | 2.3/7.7        |
| Lan et al. (2020)    | $43 \times 33.9$  | Taconic   | 3.5/28          | 20.7/20.5      | 7.07/11.31     |
| Yassin et al. (2019) | $45 \times 40$    | Rogers    | 2.4/5.5/28      | 15.8/23.5/11.3 | 1.9/3.8/7.4    |
| Nie et al. (2019)    | $72 \times 72$    | FR4       | 3.5/5.5         | 21.7/25        | 6.86/8.14      |
| This Work            | $10 \times 25$    | Rogers    | 3.5 / 23 / 38   | 10.6/9.6 / 5.0 | 2.46/5.83/5.35 |

## Conclusion

In this paper, a compact triple-band patch antenna was designed and simulated for sub-6 GHz and millimetre-wave applications. The antenna operates at 3.5 GHz, 23 GHz, and 38 GHz with simulated  $S_{11} < -10$  dB at all three bands. The compact size of  $10 \times 25$  mm is achieved by employing a diamond-shaped slot on the patch and a defected ground structure, which excite multiple resonance modes. The simulated  $-10$  dB impedance bandwidths are 0.37 GHz (10.6%), 2.2 GHz (9.6%), and 1.9 GHz (5.0%). The simulated peak gains are 2.46 dBi, 5.83 dBi, and 5.35 dBi at the three respective bands, with stable radiation patterns in simulation.

A comparative study with recent literature confirms that the proposed design offers a favourable balance of size, multiband coverage, and gain. However, the results are simulation-only, and suitability for practical 5G deployment has not been experimentally established. Future work will involve fabricating a prototype, performing experimental validation (measured  $S_{11}$ , radiation patterns, realized gain, and efficiency), and extending the design to a 4-element MIMO configuration.

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