

Design and Simulation of a 2.5 GHz Rectangular Microstrip Patch Antenna

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ABSTRACT

Existing 2.5 GHz copper/FR4 Rectangular Microstrip Patch Antennas (RMPAs) achieve good impedance matching and wider bandwidth, but they do not simultaneously provide high gain, compact patch size, and precise resonance at 2.5 GHz, which the current simulation-based study seeks to address. This presents the design and simulation of a single-element RMPA operating at 2.5 GHz using the classical transmission-line model. The antenna comprises a copper patch of 38.2 mm by 25.5 mm on a 1.6 mm FR4 substrate, a copper ground plane of 45.88 mm by 57.2 mm, and a feed offset of 1.7 mm from the patch centre. The simulation resonates at 2.502 GHz, a deviation of only 2 MHz (0.08%) from the design target, with a return loss of 10.40 dB, a Voltage Standing Wave Ratio (VSWR) of 1.91:1, and a bandwidth of 60 MHz (2.40%), satisfying the conventional -10 dB and 2 VSWR acceptance criteria. The radiation pattern exhibits a boresight gain of 5.78 dBi, a front-to-back ratio of 15.88 dB, and a half-power beamwidth of about 80° with a mismatch efficiency of 90.24%. A clean main lobe with suppressed back and side radiation confirms RMPA suitability for directional point-to-point and point-to-multipoint links. Benchmarked against two reference designs, the proposed antenna achieves exceptional resonant-frequency accuracy, strong gain, directional radiation, and low-cost simple construction. Its weaknesses are weak impedance matching and narrow bandwidth.

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INTRODUCTION

A microstrip patch antenna (MPA) is a low-profile, lightweight, cost-effective, and easily fabricated antenna widely used in various wireless systems due to its advantageous features (Idris et al., 2023; Ebisemiju et al., 2026). MPA consists of a radiating patch on one side of a dielectric substrate and a ground plane on the other. The radiating patch is generally made of conducting material such as copper or gold and usually takes regular or complex geometries. The choice of geometry impacts the antenna's performance characteristics, such as bandwidth, gain, return loss, resonant frequency, and radiation pattern (Idris et al., 2023; Abdi et al., 2025). The working principle of an MPA is based on the concept of resonant cavities; the patch and the ground plane form a resonant structure where the patch operates as a resonator. When RF signals are applied to the patch, they excite surface currents, leading to the generation of electromagnetic fields. The patch is typically designed to resonate at a particular frequency, which is determined by its dimensions and the properties of both the conducting and substrate materials.

MPAs can be fabricated using printed circuit board technology, incorporated into integrated circuits and are suitable for mobile and portable devices (Khatun et al., 2021). Their planar configuration of MPAs allows them to be easily mounted on and conform to the host surfaces, including the bodies of vehicles, aircraft, and various electronic devices. This versatility in design and manufacturing is key to the widespread adoption of MPAs in modern communication systems. One notable drawback is their narrow bandwidth, which can be restrictive for applications requiring wideband performance but advantageous for narrow-bandwidth channel-specific applications. Another limitation is their relatively low gain compared to antennas, such as horn antennas or parabolic reflectors, but can be improved along with directivity by an array of patch elements (Abdi et al., 2025). However, the resonating frequency, polarization, or radiation pattern may change dynamically in response to changes in the operational requirements. Typically, however, the radiation efficiency of an MPA can be influenced by various loss mechanisms.

Rectangular Microstrip Patch Antennas (RMPAs) offer distinct advantages over other geometrical configurations, such as circular, triangular, and hexagonal patch antennas, particularly regarding design simplicity, ease of fabrication, and performance consistency. Rectangular geometry is straightforward to analyze and implement using various design tools and software. This allows precise control of its parameters with the intention of better performance tailored toward specific applications (Abdi et al., 2025). This study seeks to design and simulate a low-cost, single-element 2.5 GHz RMPA on a copper/FR4 substrate that achieves precise resonance at the target frequency while maintaining satisfactory gain and directional radiation. It aims to address the gap in existing designs, which often achieve good impedance matching and wider bandwidth but do not simultaneously provide accurate resonance at the target frequency, high gain, and compact patch dimensions.

Operational Principle of Microstrip Patch Antenna

An RMPA works by converting electrical signals into electromagnetic waves through a resonant metal patch on a dielectric substrate. When the rectangular patch is excited by a feed line, radiation occurs primarily through fringing fields around the patch's edges. The electrical signals transform into electric field lines in the patch which terminate at the patch-air interface, and evolve into fringe fields. The fringe fields become the electromagnetic waves radiating from the patch (Mishra et al., 2015). Inside the dielectric substrate, the electric fields are usually vertical between the patch and ground. At the edges of the patch, especially along the length, this vertical electric field cannot continue straight out into the air, so it spills out sideways into the surrounding space as fringing fields. The substrate with permittivity (ϵ_r) is

suddenly adjacent to air of permittivity (ϵ_0), causing the fields to spread as electromagnetic waves into the lower-permittivity air. The generated fringe fields may be in-phase or out-of-phase. When the electric fields at the opposite edges of the patch are in-phase, the radiated waves add constructively in the far field, producing strong and directional radiation patterns, typically in the broadside direction, that is, perpendicular to the patch surface. Out-of-phase fringe fields result in poor radiation. At the patch's edges, the electric field lines curve and extend into free space. These curved, time-varying fringing fields become sources of electromagnetic radiation. In the far field, the radiation behaves like a free-space transverse electromagnetic waves, with electric and magnetic fields transverse to the direction of propagation.

The size and shape of the patch, along with the substrate's dielectric properties, determine the antenna's resonant frequency and radiation characteristics. The patch and ground plane form the resonant cavity. The patch acts like a resonator, where standing waves are set up when excited at a resonant frequency (Mishra et al., 2015). The length of the patch (L) is approximately half the wavelength ($\lambda/2$) of the desired resonant frequency in the dielectric material (Abdi et al., 2025):

$$L = \frac{\lambda}{2\sqrt{\epsilon_r}} \quad (1)$$

These fringing fields are what radiate electromagnetic waves into the surrounding space. The electromagnetic waves fringe off the top patch into the substrate, reflecting off the ground plane and radiating out into the air. The fringing fields of the antenna, which make it appear bigger than it is, are the antenna's length by its two sides (Abdi et al., 2025). Fig. 1 presents the fringe fields emanating from the patch to the ground plane.



Figure 1: Fringe Field from Patch to Ground Plane

Substrate loss occurs due to the electromagnetic energy dissipated as heat within the substrate placed between the patch and the ground plane. This dissipation is due to the imperfections in the substrate material, and is quantified by the dielectric's loss tangent ($\tan \delta$). Substrate loss leads to energy absorbed in the substrate rather than being radiated. Excessive substrate loss narrows the antenna's effective operating bandwidth. In this study, FR4, a low-cost substrate with fairly high losses yet acceptable for some applications will be utilized.

Surface wave loss refers to the electromagnetic waves trapped and guided along the substrate surface, rather than radiating into free space. This occurs when the substrate's dielectric constant (ϵ_r) and its thickness cause part of the signals to propagate as bound surface wave mode. Energy trapped as surface waves does not contribute to useful far-field radiation. Surface waves reduce the directivity of the radiation, and increasing side lobes. Using thinner substrates reduces surface loss. Electromagnetic band gap can be used to suppress

surface waves. In this study, FR4 substrate of 1.6 mm thickness and a dielectric constant of 4.4 will be utilized.

A Review of Rectangular Microstrip Patch Antennas Operating at 2.5 GHz

This section reviews only those articles on single element RMPA operating at 2.5 GHz.

Abdi et al. (2025) focused on the design, simulation, and performance evaluation of a single-element, linearly polarized RMPA operating at 2.5 GHz for modern wireless applications such as Wi-Fi, Bluetooth, and satellite uplinks, with the aim of exceeding the directivity limit of conventional FR4-based designs (>6.4 dBi) while achieving near-ideal impedance matching ($VSWR < 1.1$) without complex geometries or costly substrates. The antenna was realized on a low-cost FR4 substrate thickness 1.6 mm, with a copper radiating patch of 38 mm by 36.85 mm, a 50 mm by 50 mm ground plane, and a coaxial probe feed offset 2.1 mm from the patch centre. The initial dimensions of patch width 36.85 mm, effective dielectric constant, fringing extension of 1.67 mm, and effective and actual lengths, were computed from transmission-line model equations. These were later refined through iterative full-wave simulation and parametric optimization, until the design targets: return loss < -10 dB, bandwidth $> 4\%$ were achieved. The optimized design yielded a return loss of 27 dB at 2.5 GHz, a VSWR of 1.023, -10 dB fractional bandwidth of 4.1% (2.45–2.55 GHz). Its directivity is 6.45 dBi is barely above the 6.4 dBi limit.

Uqaili et al. (2020) presented a compact, low-cost dual-band RMPA for Wi-Fi applications, targeting simultaneous at 2.5 GHz (downlink) and 5.8 GHz (uplink) in compliance with the IEEE 802.11 WLAN standard. The study aimed to address the non-uniform radiation patterns, excessive size, and insufficient bandwidth limitations of earlier multiband designs. The antenna was printed on an FR4 epoxy substrate thickness of 1.6 mm with an overall ground plane of 44 mm by 41 mm and a radiating patch of 24 mm by 21 mm. The dual-band was engineered using two rectangular slots: first 20 mm by 4.5 mm etched into the patch and second 22 mm by 5.5 mm cut into the ground plane. These were excited via an inset microstrip feed line of 10 mm by 3 mm, an inset feed distance of 5.2 mm and a feed gap of 2 mm. The initial dimensions were derived from standard transmission-line equations, later an extensive parametric analysis conducted to systematically varying substrate material, patch dimensions, feed-line parameters, and both slot dimensions to position the resonances. The final design achieved a return loss of 29.9 dB, 100 MHz bandwidth (2.5–2.6 GHz), VSWR of 1.06, and gain of 1.36 dB at 2.5 GHz.

MATERIALS AND METHODS

Geometry of RMPA

The antenna geometry was determined using the classical design equations for rectangular microstrip patch antennas. These equations were employed to calculate the initial dimensions required to achieve resonance at the target frequency of 2.5 GHz. The resonant frequency is given by (Abdi et al., 2025):

Geometry is crucial in the determination of electromagnetic performance characteristics of RMPA, these include its resonant frequency, radiation pattern, bandwidth, return loss, and impedance. RMPA is usually a flat, rectangular conductive material strip placed on a grounded dielectric substrate. The length L_p of the rectangular patch determines the antenna's resonant frequency, while the width W_p impacts the input impedance and the radiation pattern. The basic resonant frequency f_r of the antenna can be approximated by (Abdi et al., 2025):

$$f_r = \frac{c}{2L\sqrt{\epsilon_r}} \quad (2)$$

Where c is the speed of light. The effective dielectric constant accounts for the fringing fields around the patch's periphery and is generally slightly less than the dielectric constant of the substrate, due to the presence of air around the patch. The substrate's thickness h influences the effective dielectric constant and is calculated as (Abdi et al., 2025):

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W_p} \right)^{-\frac{1}{2}} \quad (3)$$

The effective electrical length of the patch was corrected by accounting for the fringing-field length extension. The presence of fringing fields makes the patch electrically larger than its physical dimensions, affecting the resonant frequency and the impedance bandwidth. The input impedance Z_{in} depends on the conductance G and susceptance B of the patch and was determined using the transmission line model given by:

$$Z_{in} = \frac{1}{G + jB} \quad (4)$$

The conductance and susceptance influenced by the patch's width, the effective dielectric constant, the operating frequency and the wavelength in free space λ_0 . The conductance and susceptance can be expressed as:

$$G = \frac{W_p}{120\lambda_0} \left(\frac{\epsilon_r + 1}{2} \right) \quad (5)$$

$$B = \frac{W_p}{120\lambda_0} \left(\frac{\epsilon_r - 1}{2} \right) \quad (6)$$

The fringing-field length extension (ΔL) was calculated using (Abdi et al., 2025):

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W_p}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W_p}{h} + 0.8 \right)} \quad (7)$$

The width, actual and effective patch length are (Idris et al., 2023; Abdi et al., 2025; Uqaili et al., 2020; Ramineni & Nimmala, 2024):

$$W_p = \frac{c}{2f_r} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (8)$$

$$L_p = \frac{c}{2f_r \sqrt{\epsilon_{eff}}} \quad (9)$$

$$L_{eff} = \frac{c}{2f_r \sqrt{\epsilon_{eff}}} + 2\Delta L \quad (10)$$

The length L_g and width W_g of the ground plane are usually the same as the length L_s and width W_s of the substrate. This is to provide adequate support for the patch and ensure sufficient radiation. The relationship for estimating these dimensions are (Ramineni & Nimmala, 2024):

$$L_g = L_p + 6h \quad (11)$$

$$W_g = W_p + 6h \quad (12)$$

Choice of Geometry

The RMPA features a rectangular structure, typically chosen for its simplicity and effective radiation characteristics. The patch is a critical component in ensuring efficient transmission and reception at this frequency. The design began with assigning values for the dimensions of the dielectric substrate, the radiating patch, and the ground plane. However, these values were optimized during simulation to yield efficient radiation characteristics. Using the above equations, the patch's width and length, the ground plane's width and length and fringe extension are 36.52, 28.24, 37.84, 46.12, and 1.478 mm, respectively. However, these values were adjusted to 38.2, 25.5, 57.2, 45.9 and 1.478 mm, respectively.

These dimensions resonate at exactly 2.502 GHz. The patch width affects the input impedance and bandwidth, while the length determines the resonant frequency. The patch and the ground plane are made of 0.25 mm copper thickness, a common conductive material in antenna

design due to its excellent electrical conductivity, which minimizes resistive losses and enhances efficiency. An FR4 substrate of thickness 1.6 mm and relative dielectric constant of 4.4 was selected because it provides a practical compromise between cost, manufacturability, and acceptable electrical performance for operation at 2.5 GHz. The corresponding effective dielectric constant obtained from the design calculations was 4.4. The FR4 substrate with a thickness of 1.6 mm and an effective dielectric constant of 4.4 was selected to overcome substrate and surface losses and to influence the antenna size, impedance matching, and bandwidth. The length and width of the ground plane are 45.9 mm and 57.2 mm, respectively, to provide a return path for currents and modify the antenna's radiation pattern and impedance characteristics. A larger ground plane generally improves performance, but at the cost of increasing its size and weight. The feed point offset set at 1.7 mm from the center is crucial for impedance matching. This placement helps achieve a good match between the antenna and the feed line, reducing reflections and ensuring efficient power transfer. The above geometries and equations were written in script, simulated and optimized in MATLAB R2023a.

RESULTS AND DISCUSSION

Fig. 2 presents the simulated RMPA which is composed of a 1.6 mm thick FR4 substrate with an effective dielectric constant of 4.4, placed between a patch and a ground plane of copper. The length and width of the patch are 25.5 mm and 38.2 mm, while those of the ground plane are 45.88 mm and 57.2 mm, respectively. These were chosen using the set of classical equations to ensure the antenna resonates at 2.5 GHz. The patch feedline at an offset of 1.7 mm was carefully chosen because it influenced the overall antenna performance.

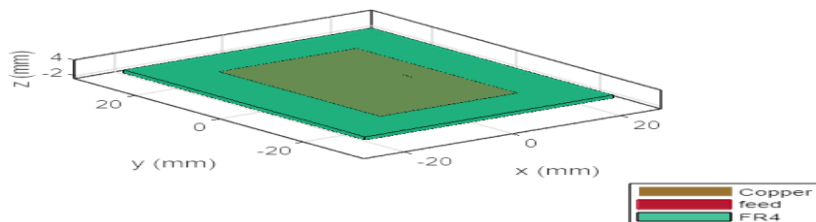


Figure 2: Simulated Microstrip Patch Antenna

Figure 3 shows the 3D radiation pattern of the simulated RMPA with a maximum gain of 5.78 dBi at the boresight and a minimum gain of -10.1 dBi in the back lobe which is significantly suppressed to improve the forward gain. The front-to-back ratio is 15.88. The antenna is highly

directive with most of the energy radiated in the direction of the main lobe. This antenna is suitable for applications requiring directed radiation, such as point-to-point and point-to-multipoint communications where high gain in some specific direction are beneficial.

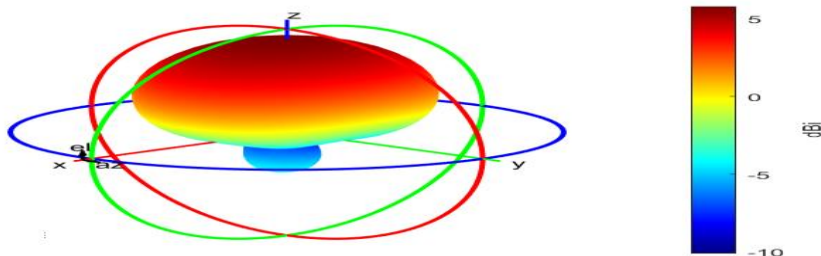


Figure 3: 3D Radiation Pattern

The elevation radiation pattern is shown in Fig. 4 with a broadside gain of 5.78 dBi which gradually reduces on both sides of the pattern and reaching -3.544 dBi in the back lobe. In the plot, the gain (dBi) is given as a function of angle from 0° to 360° , with a fixed azimuth angle of 0° . The pattern is asymmetric while showing that the antenna radiates more strongly in the boresight direction (90°) than in the opposite direction (270°). A significant

drop in gain at 270° indicates a high front-to-back ratio which suggests good directionality. There are no significant side lobes indicating clean main lobe radiation. The gain decreases below 0 dBi at angles near 0° and 180° , suggesting radiation nulls in those directions. The 3 dB beamwidth appears to be between 50° and 130° , giving an approximate beamwidth of 80° .

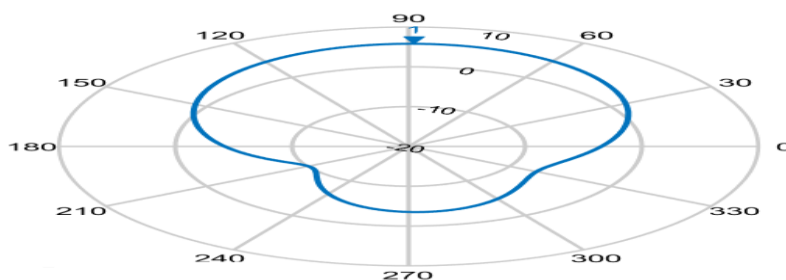


Figure 4: Elevation Radiation Pattern

The cloverleaf shape azimuth radiation pattern is shown in Fig. 5, with the elevation angle fixed at 0° . The gain varies between approximately -3.23 dBi and -4.037 dBi. The peak gain is at 30° . Unlike the elevation pattern the azimuth pattern does not show a strong directional peak but the gain remains in the negative dBi range indicating weak horizontal radiation and this is usual for patch antennas designed for broadside radiation. Noticeable

nulls are found approximately at 90° , 180° , and 270° , with gain around -4.037 dBi. The pattern appears fairly symmetrical in four quadrants, which suggests uniform performance in those directions. The pattern is symmetrical in the ranges 0° - 180° and the 90° - 270° axes, means the antenna has a balanced radiation pattern in the azimuth plane suitable for applications requiring coverage in multiple specific directions.

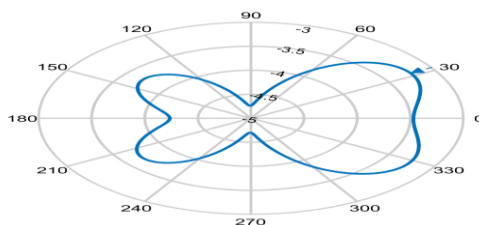


Figure 5: Azimuth Radiation Pattern

Figure 6 shows the gains of elevation and azimuth plotted against angle around the antenna. The elevation has a peak at about 6 dBi showing strong forward radiation and minimal side lobes while the azimuth has a peak at -4 dBi showing omnidirectional in the azimuthal plane. Higher

gain in a particular direction increases the effective range and improves signal-to-noise ratio in that direction. This minimizes radiation in unwanted directions and curbs interference in dense wireless environments.

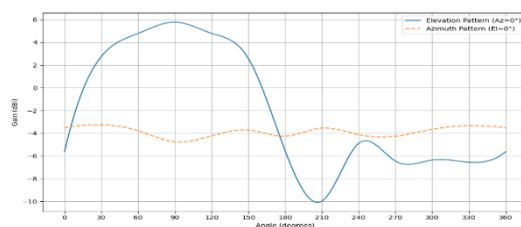


Figure 6: Plot of Elevation and Azimuth Gains versus Theta Angle

The scattering parameters are critical for understanding the antenna performance regarding reflection and transmission at a specific resonant frequency. Fig. 7 presents the S_{11} which shows a dip at 2.502 GHz that confirming the resonant behavior at this frequency. The

return loss is 10.40 dB indicating a good matching efficiency of 90.24%. The bandwidth is about 60 MHz which extends from approximately 2.47 GHz to 2.53 GHz. The VSWR is 1.91:1, indicating a fairly good impedance matching.

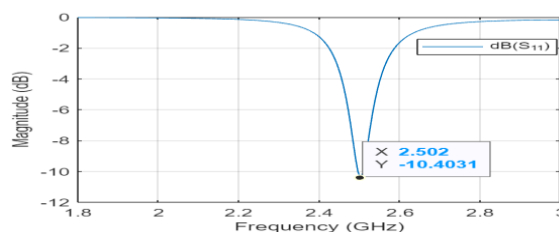


Figure 7: S-Parameter

Comparison with Previous Results

The three antenna designs share some common materials and structural platform, which makes their performance differences attributable to geometry and design strategy. All employ copper as the radiating conductor on a 1.6 mm-thick FR4 substrate, these are most widely available and economical combination for patch antenna research, suitable for low-cost mass production. The three are RMPA designed for the 2.5 GHz sub-band but resonating at 2.502 GHz, ~2.53 GHz, and ~2.55 GHz, respectively, satisfy the accepted impedance-matching criterion of -10 dB return loss, with VSWR values below 2.0. Their fractional bandwidths are similarly narrow ranging from 2.40 %–4.10 %, which is characteristic of conventional single-feed patches on low-permittivity substrates. Similarly, their gains ranging from 1.36 dBi to 6.45 dBi fall within the expected range for this antenna class. This commonality establishes a fair basis for the pairwise comparisons that follow.

Abdi et al. (2025) outperform the current design in matching quality, bandwidth, and marginally in gain. Their return loss of 27.0 dB and VSWR of 1.023 indicate a better impedance match with only about 0.2% of the incident power reflected, compared with the current design's 10.40 dB and 1.91, representing about 9.1 % incident power reflected. This is adequate but with minimal margin above the acceptance threshold. Their bandwidth is also better, at 4.10 % (104 MHz) against 2.40 % (60 MHz), and their gain of 6.45 dBi exceeds the current 5.78 dBi by 0.67 dB. Conversely, the current design demonstrates a decisive advantage in frequency

accuracy: it resonates at 2.502 GHz, only 2 MHz (0.08 %) from the 2.5 GHz target, whereas Abdi et al. (2025) resonates at about 2.53 GHz, a 30 MHz (1.2 %) deviation. This deviation is fifteen times larger than that of the current design. The current design also achieves a more compact patch, 974 mm² compared to 1,400 mm², which is 30% reduction. The ground plane configurations also differ significantly: Abdi et al. (2025) have more compact 48.31 mm² compare to the current 2624.34 mm². Better matching and bandwidth are on one side of Abdi et al. (2025) while on-target resonance and compactness on the current study.

Uqaili et al. (2020) similarly excel in impedance matching and bandwidth: their return loss of 29.90 dB and VSWR of 1.06 (0.1 % power reflection) are the better compared to 10.40 and 1.91 (9.1% power reflection). The 4.00 % (102 MHz) bandwidth nearly doubles that of the current design. The reference antenna also has a more compact: 504 mm² compared to 974.1mm², about 48 % smaller than the current design's, making it attractive where board space is constrained. However, the current design holds two clear advantages. First, its gain of 5.78 dBi is more than 4 dB higher than Uqaili et al.'s (2020) 1.36 dBi. This indicates substantially superior radiation performance for link-budget-critical applications. Second, the current design achieves far better frequency accuracy, with a resonance error of only 2 MHz (0.08 %) against Uqaili et al.'s (2020) 50 MHz (2.0 %). Uqaili et al. (2020) prioritize matching, bandwidth, and miniaturization at the cost of gain and on-target

resonance, but the current design trades matching margin and bandwidth for exact 2.5 GHz resonance and gain.

Table 1: Comparison of RMPA operating at 2.5 GHz with the Current Study

Parameter	Abdi et al. (2025)	Uqaili et al. (2020)	Current
Conductor	Cu	Cu	Cu
Substrate	FR4	FR4	FR4
Patch Width (mm)	36.85	24.00	38.20
Patch Length (mm)	38.00	21.00	25.50
Ground Width (mm)	28.93	44.00	45.88
Ground Length (mm)	1.67	41.00	57.20
Substrate Thickness (mm)	1.60	1.60	1.60
Return Loss (dB)	27.00	29.90	10.40
VSWR	1.023	1.06	1.91
Bandwidth (%)	4.10	4.00	2.40
Resonant Frequency (GHz)	About 2.53	Around 2.55	2.502
Resonance Error (MHz)	30	50	2
Resonance Error (%)	1.2	2.0	0.08
Gain (dBi)	6.45	1.36	5.78

CONCLUSION

Although existing 2.5 GHz RMPA designs on copper/FR4 substrates have achieved strong impedance matching and wider bandwidths, they have not simultaneously delivered high gain, compact patch dimensions, and precise resonance at the 2.5 GHz target. The current study addresses part of this gap by achieving a resonance error of only 2 MHz (0.08%), a gain of 5.78 dBi, and a 30% smaller patch area. However, further refinements are required to address its weak impedance matching and narrow bandwidth before fabrication and deployment.

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