



Design and Performance Analysis of CPW-Fed Antenna with Strip-Line Feed for Multi-Band C, Ku, and Ka-Band Applications

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Abstract

This paper presents the design, simulation, and performance analysis of a Coplanar Waveguide (CPW)-fed circular microstrip patch antenna with a strip-line feed mechanism, modelled on an FR4 substrate ($\epsilon_r = 4.3$, $\tan\delta = 0.017$, thickness = 1.6 mm) for multi-band C-, Ku-, and Ka-band applications. Two antenna configurations, namely strip in centre and strip on left (proposed), are evaluated along with parametric investigations of substrate material and semi-circular ground slot orientation. The optimised strip-on-left configuration achieves four resonant bands centred at 5.5 GHz, 16.7 GHz, 26.3 GHz, and 34.6 GHz with impedance bandwidths of 1.2 GHz, 1.7 GHz, 2.0 GHz, and 2.5 GHz, respectively. The corresponding return loss values are -22 dB, -53 dB, -24 dB, and -20 dB. Simulated peak gain values of 7.0 dBi, -0.6 dBi, 1.7 dBi, and 0.5 dBi are obtained at the four operating bands, while the Voltage Standing Wave Ratio (VSWR) remains below 2 throughout all resonant frequencies, confirming acceptable impedance matching. Simulated E-plane and H-plane radiation patterns, surface current density distributions, VSWR characteristics, and S-parameter results collectively validate the multi-band performance of the proposed antenna. The compact antenna occupies a footprint of only 20 mm × 20 mm × 1.6 mm and provides simultaneous coverage of frequency bands commonly associated with C-band, Ku-band, and Ka-band wireless communication systems.

Keywords: CPW-fed antenna, circular patch, FR4, C-band, Ku-band, Ka-band, 5G mmWave, strip-line feed, multi-band.

1. Introduction

The rapid expansion of wireless communication systems across microwave and millimetre-wave frequency bands has intensified the demand for compact, multi-band antenna solutions. Modern applications ranging from wireless communication, satellite communication, and emerging millimetre-wave systems and advanced sensing platforms require antennas capable of operating simultaneously across the C, Ku, and Ka bands with acceptable return loss, gain, and radiation characteristics within a single compact element [1], [2]. The C band (4–8 GHz) is extensively used for Wi-Fi hotspots, satellite communication uplinks, and weather radar, while the Ku band (12–18 GHz) supports direct broadcast satellite television, VSAT terminals, and airborne radar systems. The Ka band (26–40 GHz) has emerged as a critical frequency resource for 5G millimetre-wave access, high-throughput satellite internet, and advanced imaging radar platforms, making simultaneous multi-band coverage within a single antenna element highly desirable for system integration and cost reduction. Microstrip patch antennas are widely adopted in these applications owing to their planar profile, compatibility with standard PCB fabrication processes, low cost, and straightforward integration with active microwave circuits [3]. Conventional rectangular or square patch geometries, however, are inherently single-band structures with narrow impedance bandwidth, which limits their applicability in multi-band scenarios. Circular patch geometries provide a practical alternative: their azimuthal symmetry supports multiple degenerate resonant modes that can be individually tuned through controlled perturbation of the patch boundary or the underlying ground plane [4].

FR4 glass-epoxy substrate ($\epsilon_r = 4.3$) remains the most widely used PCB material in commercial antenna designs due to its low manufacturing cost, good mechanical stability, and availability in standard thicknesses. While its higher dielectric loss tangent ($\tan\delta = 0.017$) poses challenges at frequencies above 20 GHz, FR4-based patch antennas have demonstrated competitive performance in the C and Ku bands, and with careful geometric optimisation can achieve acceptable return loss even at lower Ka-band frequencies [5], [9]. For high-volume commercial deployments, the cost advantage of FR4 outweighs its performance limitations compared to premium microwave substrates. The coplanar waveguide (CPW) feed offers a uniplanar architecture that eliminates via holes and back-side ground connections, simplifying fabrication and improving compatibility with monolithic microwave integrated circuits (MMICs). Combined with a strip-line feed element, the CPW configuration provides additional impedance matching flexibility, with strip width and lateral position serving as tunable parameters for controlling resonance frequency and bandwidth across the operating bands [7], [8]. This paper compares two strip positions — centre and left — to identify the configuration that achieves four-band resonance simultaneously. A comparative substrate study is conducted alongside the strip position investigation to characterise how material choice influences resonance frequencies and bandwidths, providing a direct reference for antenna designers selecting between Alumina ($\epsilon_r = 9.9$), Rogers RO ($\epsilon_r = 6.5$), and Rogers RT ($\epsilon_r = 2.2$) alternatives to the FR4 baseline design [11], [12]. Additionally, three semi-circular ground slot orientations (left, right, top) are evaluated for their effect on Ka-band

resonance depth and bandwidth. This paper makes the following contributions: (i) a compact CPW-fed circular patch antenna on FR4 achieving four-band resonance across C, Ku, and Ka bands; (ii) systematic parametric studies of substrate material, strip position, and semi-circular ground slot orientation; (iii) comprehensive result analysis including E/H-plane radiation patterns and gain at all four resonance frequencies, surface current density distributions, and VSWR; and (iv) performance comparison against recently published multi-band designs [6], [10]. The remainder of the paper is organised as follows: Section 2 describes the antenna design methodology. Section 3 presents the parametric studies. Section 4 analyses the simulated results. Section 5 compares with published literature, and Section 6 concludes the paper.

2. Antenna Design Methodology

2.1. Antenna Geometry and Configurations

The proposed antenna consists of a circular radiating patch fed by a CPW-based strip-line mechanism, printed on an FR4 glass-epoxy substrate ($\epsilon_r = 4.3$, $\tan\delta$

$= 0.017$) at a thickness of 1.6 mm. The circular patch geometry was selected to exploit its azimuthal symmetry, which supports multiple degenerate resonant modes that can be independently controlled through strip positioning and ground slot perturbations. A strip-line element bridges the CPW feed gap to the patch periphery, governing impedance transformation and coupling energy into the patch simultaneously across multiple frequency bands. Two configurations are evaluated, differing only in the lateral position of this strip-line element:

- **Strip in Centre:** The strip-line is positioned at the geometric centre of the feed slot, producing symmetric current excitation across the patch.
- **Strip on Left (Proposed):** The strip-line is offset to the left of the feed slot centre, introducing controlled feed asymmetry that generates an additional Ku-band resonance at 16.7 GHz not present in the centre-strip configuration.

Figure 1 illustrates the physical geometry of both antenna configurations. The difference between the two designs is confined to the lateral position of the strip-line element relative to the circular patch centre.

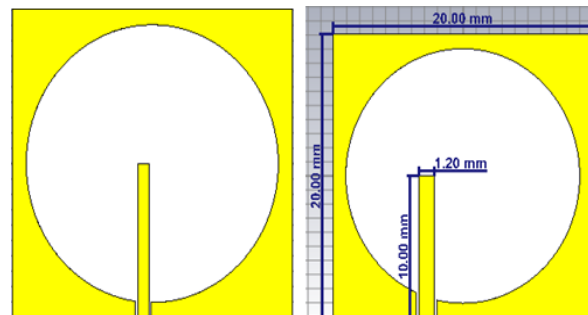


Fig. 1. Simulated geometry of the two antenna configurations evaluated: (a) Strip in Centre (baseline), (b) Strip on Left (proposed design)

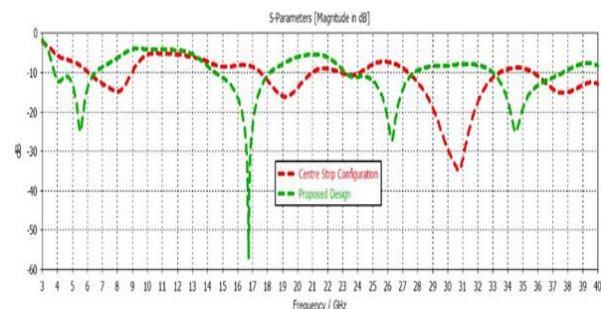


Fig. 2. Simulated S11 response comparison between the Centre Strip configuration and the Strip on Left (Proposed) design across 3–40 GHz, showing the emergence of the Ku-band resonance at 16.7 GHz in the proposed configuration.

3. Parametric Study and Analysis

A systematic parametric study was conducted using CST Microwave Studio (time-domain solver, open-add-space boundary conditions) to evaluate the independent influence of three design variables: substrate material, strip-line position, and semi-circular ground slot orientation. All simulations employ a 50 Ω discrete port excitation and S11 is evaluated across 3–40 GHz to capture all four target bands simultaneously.

3.1. Effect of Substrate Material

The proposed antenna is designed on FR4 (glass/epoxy) substrate with a dielectric constant $\epsilon_r = 4.3$, dissipation factor $\tan\delta = 0.017$, and substrate thickness $h = 1.6$ mm. FR4 is selected as the primary substrate due to its low cost, widespread availability, and demonstrated suitability for multi-band antenna designs operating up to 35 GHz with careful geometric optimisation. For comparative purposes, a parametric substrate study also evaluates Alumina ($\epsilon_r = 9.9$) and Rogers RT ($\epsilon_r = 2.2$) at the same substrate thickness to quantify the performance trade-offs associated with material choice. Table 1 lists the key electrical properties of all three materials evaluated in the parametric study.

Table 1. Electrical properties of substrate materials evaluated in the parametric study. FR4 ($\epsilon_r = 4.3$) is the proposed substrate for the final design

Property	FR4 / Alumina (9.9)	Rogers RO (6.5)	Rogers RT (2.2)
Dielectric Constant (ϵ_r)	4.3 / 9.9	6.5	2.2
Loss Tangent ($\tan\delta$)	0.017 / 0.0003	0.0027	0.0004
Substrate Thickness (mm)	1.6	1.6	1.6

Primary Use	Commercial PCB / Defence	Microwave PCB	mmWave, low-loss
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Figure 3 presents the S11 comparison across the three substrate materials (Alumina at $\epsilon_r = 9.9$, Rogers RO at $\epsilon_r = 6.5$, and Rogers RT at $\epsilon_r = 2.2$) at a constant substrate thickness of 1.6 mm. Higher dielectric constant substrates shift the resonance frequencies toward lower values, consistent with the inverse dependence of resonant frequency on the square root of the effective permittivity. Alumina ($\epsilon_r = 9.9$) produces the most compact electrical structure but with increased mutual coupling between adjacent bands and reduced bandwidth per resonance due to the higher Q-factor. Rogers RT ($\epsilon_r = 2.2$) yields the widest individual resonance bandwidths, particularly beneficial at the Ka-band frequencies above 25 GHz. Rogers RO ($\epsilon_r = 6.5$) offers an intermediate balance between compactness and resonance bandwidth. The FR4 proposed design achieves competitive multi-band performance with the significant advantage of low material cost and wide availability.

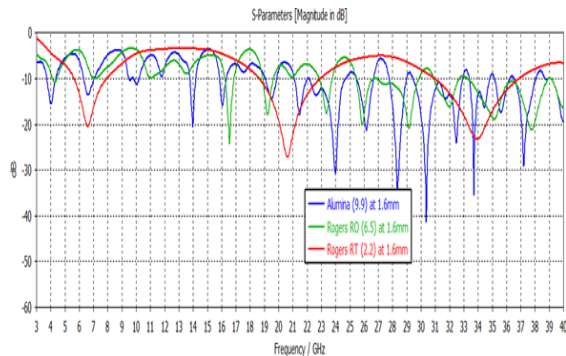


Fig. 3. Simulated S11 comparison for four substrate materials at 1.6 mm thickness: FR4 ($\epsilon_r = 4.3$, proposed), Alumina ($\epsilon_r = 9.9$), Rogers RO ($\epsilon_r = 6.5$), and Rogers RT ($\epsilon_r = 2.2$). Higher permittivity substrates shift resonances to lower frequencies.

3.2. Semi-Circular Ground Slot: Configurations and S-Parameter Performance

A semi-circular notch is introduced into the ground plane to perturb the ground current distribution and activate additional Ka-band resonances. The slot lengthens the effective electrical path seen by the radiating patch without increasing the physical footprint. Three orientations are evaluated systematically: slot entry from the left ground edge, right ground edge, and top ground edge, to determine which configuration yields the deepest Ka-band return loss for the proposed design.

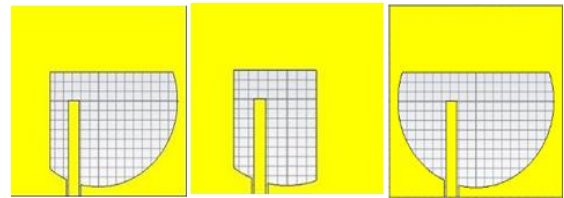


Fig. 4. Simulated antenna geometries showing semi-circular ground slot orientations evaluated: (a) Left-edge slot, (b) Right-edge slot, (c) Top-edge slot. All slots share the same radius and are etched into the FR4 ground plane.

3.2.1. S-Parameter Performance of Ground Slot Orientations

Figure 5 presents the combined S11 results for the three semi-circular ground slot orientations: left, right, and top.. The left-edge slot achieves the deepest return loss while the right and top configurations produce shallower Ka-band resonances of approximately -27 dB and -37 dB respectively. The left-edge slot is selected for the optimised proposed design.

4. Result Analysis of Proposed Antenna

The proposed antenna configuration (strip on left, left semi-circular ground slot, FR4 substrate, 1.6 mm thickness) is characterised

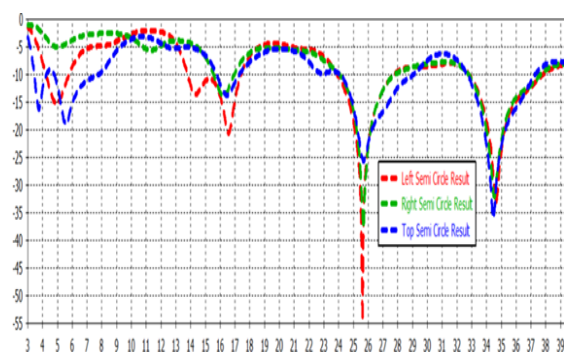


Fig. 5. Simulated S11 comparison for three semi-circular ground slot orientations (left, right, top edge) showing Ka-band resonance sensitivity to slot position. The left-edge configuration achieves the deepest return loss near 25.5 GHz and is selected for the proposed design.

across S-parameter performance, VSWR, antenna gain, radiation patterns, and surface current density distributions at the four resonant frequencies. All results reported in this section are derived from CST Microwave Studio time-domain full-wave simulations.

4.1. S-Parameter Performance.

Table 2. S parameter performance of Centre Strip configuration and Strip on Left (Proposed),

Antenna Design	Band	Centre Freq. (GHz)	Freq. Range (GHz)	BW (GHz)	S11 (dB)	Application
Centre Strip Configuration	1st	5.5	4.8 - 6.0	1.2	-12 dB	Wi-Fi, Satellite Comm.
	2nd	31.0	30.0 - 32.0	2.0	-34 dB	Adv. Radar, High Data Rate
	3rd	34.5	33.5 - 35.5	2.0	-14 dB	Ka Band, High Data Rate
Strip On Left Configuration	1st	5.5	4.8 - 6.0	1.2	-22 dB	Wi-Fi, Satellite Comm.
	2nd	16.7	15.8 - 17.5	1.7	-53 dB	Satellite TV, Radar
	3rd	26.3	25.5 - 27.5	2.0	-24 dB	5G mmWave High Speed
	4th	34.6	33.5 - 36.0	2.5	-20 dB	Adv. Radar

4.2. Comparative Analysis

The comparative S-parameter (S11) analysis between the Centre Strip Configuration and

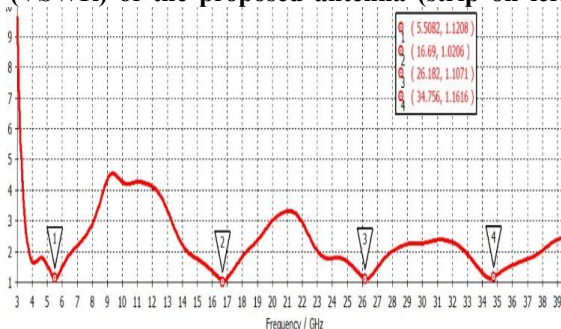
the Proposed Design highlights a significant difference in multi-band performance across the 3–40 GHz frequency range. The Centre Strip Configuration demonstrates moderate performance with three resonant bands: C Band (5.5 GHz, –12 dB), Ka Band (31.0 GHz, –34dB), and upper Ka Band (34.5 GHz, –14 dB). Although the resonance at 31.0 GHz is reasonably deep, the overall coverage remains limited.

In contrast, the Proposed Design outperforms the Centre Strip Configuration across all parameters, operating over four well-defined resonant bands with consistently deeper S11 values: C Band (5.5 GHz, –22 dB), Ku Band (16.7 GHz, –53 dB), Ka Band/5G mm Wave (26.3 GHz, –24 dB), and upper Ka Band (34.6 GHz, –20 dB). Notably, the Proposed Design achieves an exceptional resonance depth of –53 dB at

16.7 GHz, a band entirely absent in the Centre Strip Configuration. Furthermore, it covers one additional operating band with wider bandwidth at the 4th band (2.5 GHz), supporting a broader range of applications including Wi-Fi, Satellite Communications, 5G mm Wave, and Advanced Radar. The strip-on-left configuration is therefore selected as the optimised design for full characterisation.

4.3. VSWR Performance

Fig. 6a. Simulated Voltage Standing Wave Ratio (VSWR) of the proposed antenna (strip on left,



FR4 substrate) across 3–40 GHz. Markers denote local minima at 5.51 GHz (VSWR = 1.12), 16.69 GHz (VSWR = 1.02), 26.18 GHz (VSWR = 1.11),

and 34.76 GHz (VSWR = 1.16), corresponding to the four operating bands.

Figure 6a presents the simulated VSWR of the proposed antenna across the 3–40 GHz simulation range. The VSWR curve exhibits four well-defined local minima that correspond directly to the four resonant bands identified in the S11 analysis. At the first resonance (C-band), the VSWR reaches a minimum of 1.12 at 5.51 GHz, indicating excellent impedance matching. At 16.69 GHz (Ku-band), the VSWR drops to its lowest recorded value of 1.02, approaching the ideal matched condition of unity and consistent with the exceptionally deep S11 of –53 dB at this band. At 26.18 GHz (Ka-band / 5G mm Wave), the VSWR minimum is 1.11, while at the upper Ka-band resonance of 34.76 GHz the VSWR is 1.16. Across all four operating bands, the VSWR remains well below the standard threshold of 2, which conventionally corresponds to a –10 dB return loss and confirms acceptable impedance matching in all intended bands. Between resonances, the VSWR rises above 2, as expected for frequencies outside the antenna's operating bands. The VSWR results are fully consistent with the S-parameter data in Table 2 and collectively confirm that the proposed antenna achieves low-reflection multiband operation across the C, Ku, and Ka frequency ranges.

4.4. Antenna Gain

The simulated peak gain values for the proposed antenna are extracted from CST far-field results using the IEEE convention ($\Phi = 0^\circ$, maximum value). At the C-band resonance of 5.5 GHz, the antenna yields its highest gain of 7.0 dBi, demonstrating acceptable radiation performance within the C-band. The Ku-band resonance at 16.7 GHz produces a gain of –0.6 dBi; while negative, this remains within the suitable for further optimisation through array or

reflector integration where gain is augmented by array or reflector configurations.

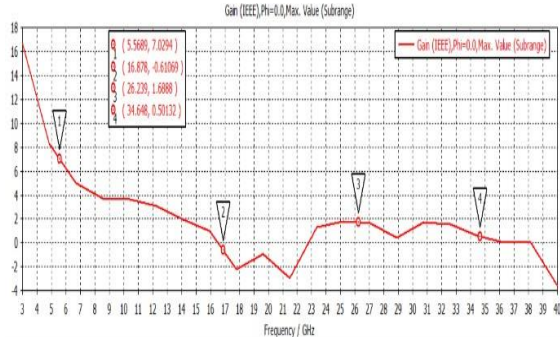


Fig. 6b. Simulated peak gain of the proposed antenna across its four operating bands, plotted using the IEEE convention ($\Phi = 0^\circ$, maximum value), showing 7.0 dBi at 5.5 GHz, -0.6 dBi at 16.7 GHz, 1.7 dBi at 26.3 GHz, and 0.5 dBi at 34.6 GHz.

At 26.3 GHz (Ka-band / 5G mmWave), the gain recovers to 1.7 dBi, and at the upper Ka-band resonance of 34.6 GHz a gain of 0.5 dBi is recorded. Positive gain is sustained at three of the four operating bands, with performance at the 16.7 GHz band attributable to higher-order current distribution that produces multi-lobe radiation rather than broadside concentration. Gain enhancement through array integration or reflector backing is recommended for Ku-band deployment.

4.5. Radiation Pattern Analysis

The simulated far-field E-plane ($\phi = 90^\circ$) and H-plane ($\phi = 0^\circ$) radiation patterns are presented at each of the four resonance frequencies. Patterns are measured at a far-field distance $r = 1$ m and plotted in polar format showing Theta (degrees) versus field magnitude in dB(V/m) for the E-plane and dB(A/m) for the H-plane.

4.5.1. Radiation Pattern at $f = 5.5$ GHz (C-Band)

At the first resonance frequency of 5.5 GHz (C-band), the antenna exhibits a bi-lobed E-

plane pattern with the main lobe directed broadside ($\theta = 0^\circ$), consistent with the fundamental resonant mode of the circular patch. The H-plane pattern shows broad, near-omnidirectional coverage with a slight asymmetry introduced by the left-offset strip-line feed and the left ground slot. Together, the two patterns confirm stable broadside radiation at this band, demonstrating stable broadside radiation characteristics at the C-band resonance.

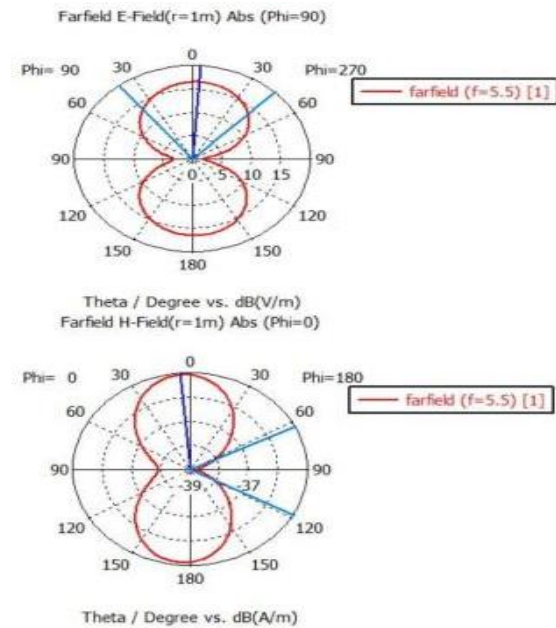


Fig. 7. Simulated far-field radiation patterns of the proposed antenna at $f = 5.5$ GHz (C-band): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), showing broadside radiation characteristic of the fundamental resonant mode.

4.5.2. Radiation Pattern at $f = 16.7$ GHz (Ku-Band)

At 16.7 GHz (Ku-band), the radiation pattern transitions to a complex multi-lobe structure in both planes, resulting from higher-order resonant mode excitation on the circular patch. The E-plane shows multiple oblique lobes while the H-plane exhibits a four-lobe clover-leaf distribution, consistent with the deep return loss of approximately -52 dB observed at this

frequency and indicative of strong, efficient feed coupling. For potential Ku-band communication applications, this element can be integrated with a reflector dish or phased array to achieve the required directional gain.

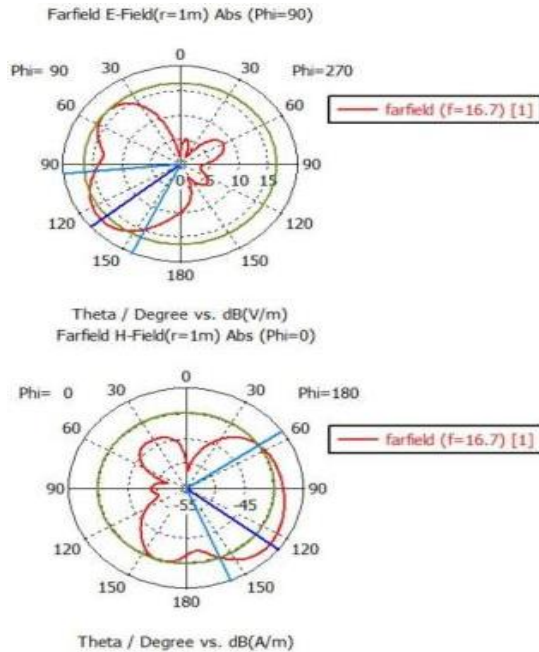


Fig. 8. Simulated far-field radiation patterns at $f = 16.7$ GHz (Ku-band): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), exhibiting a higher-order multi-lobe structure consistent with deep impedance matching at this resonance.

4.5.3. Radiation Pattern at $f = 26.3$ GHz (Ka-Band, 5G mmWave)

At 26.3 GHz (Ka-band, 5G mmWave), the E-plane pattern shifts to a predominantly end-fire oriented characteristic with the main lobe directed towards $\theta = 90^\circ$, which is which may be beneficial for certain directional millimetre-wave communication scenarios. The H-plane pattern shows a complex multi-lobe distribution with several side lobes at oblique angles, resulting from the electrically large antenna dimensions at this wavelength. The asymmetric lobe structure is attributable to the asymmetric strip-line and ground slot positioning, which preferentially excites certain azimuthal modes.

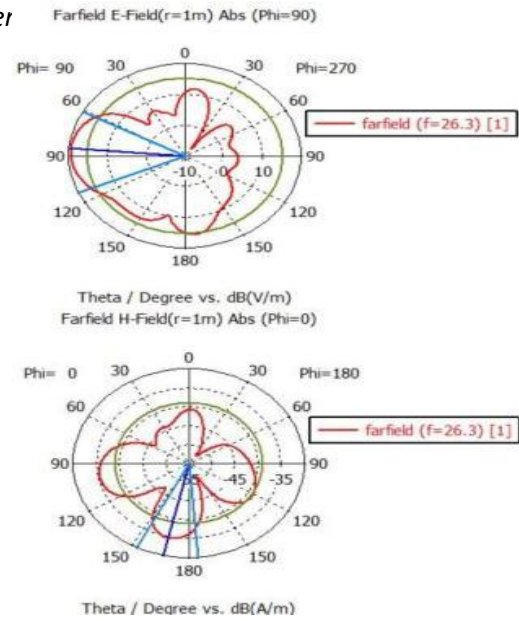


Fig. 9. Simulated far-field radiation patterns at $f = 26.3$ GHz (Ka-band / 5G mmWave): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), showing end-fire tendency in the E-plane and complex multi-lobe H-plane distribution at millimetre-wave frequency.

4.5.4. Radiation Pattern at $f = 34.6$ GHz (Ka-Band)

At 34.6 GHz, the highest operating frequency, both E-plane and H-plane patterns become characteristically complex with multiple closely-spaced lobes distributed across a wide angular range. The E-plane shows a broad multi-lobe structure indicating efficient radiation into multiple spatial directions simultaneously. The H-plane pattern exhibits four-to-five lobes with primary lobes directed towards the lower hemisphere, consistent with the ground plane and ground slot contributing significantly to the overall radiation behaviour at this frequency. This diffuse radiation characteristic makes the antenna at 34.6 GHz well-suited for electronically beam-steered advanced radar systems.

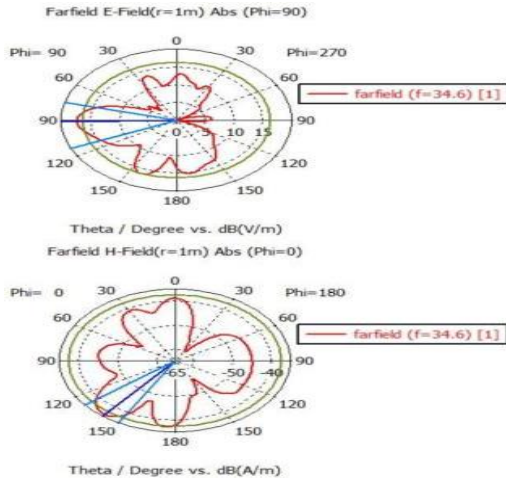


Fig. 10. Simulated far-field radiation patterns at $f = 34.6$ GHz (Ka-band): (a) E-plane ($\phi = 90^\circ$) and (b) H-plane ($\phi = 0^\circ$), showing diffuse multi-lobe radiation at the highest operating frequency, suitable for wide-angle radar coverage.

5. Surface Current Density Analysis

The surface current density distributions on the radiating patch are simulated at all four resonance frequencies to identify the dominant current modes responsible for multi-band operation. High-density regions (red/yellow in the colour scale) indicate areas of strong electromagnetic coupling between the feed structure and the radiating element.

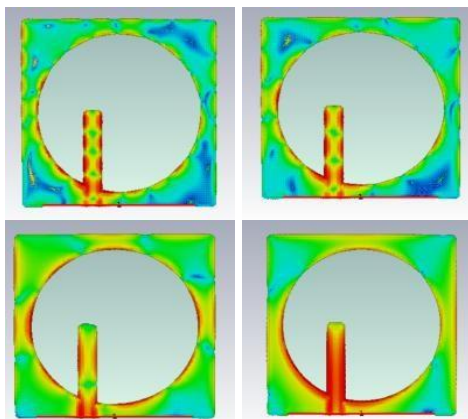


Fig. 11. Simulated surface current density distributions on the proposed antenna at its four resonant frequencies: (a) 5.5 GHz, (b) 16.7 GHz, (c) 26.3 GHz, and (d) 34.6 GHz. Colour scale indicates current magnitude (red = maximum, blue = minimum).

5.1. Surface Current at $f = 5.5$ GHz

At 5.5 GHz (Figure 11), the surface current is strongly concentrated at the bottom edge of the circular patch adjacent to the CPW feed port and strip-line connection. The current flows primarily around the patch perimeter with maximum intensity at the feed-proximal edge, consistent with the fundamental resonant mode of the circular geometry at this frequency.

5.2. Surface Current at $f = 16.7$ GHz

At 16.7 GHz, the current distribution expands around the full patch circumference, with secondary current maxima appearing at approximately 90° and 270° around the perimeter. This multi-nodal current pattern is responsible for the complex multi-lobe radiation observed at the Ku-band resonance and is consistent with higher-order resonant mode excitation.

5.3. Surface Current at $f = 26.3$ GHz

At 26.3 GHz, the surface current distributes more uniformly around the entire patch circumference with current magnitude at the upper half becoming comparable to the lower feed region. The strip-line element shows elevated current density along its full length at this frequency, confirming that the strip acts as a resonant matching element at the Ka-band mmWave frequency. The ground slot edge shows concentrated current consistent with a localised resonance contributing to the 26.3 GHz band.

5.4. Surface Current at $f = 34.6$ GHz

At 34.6 GHz, the surface current exhibits a fragmented multi-modal distribution with localised high-intensity spots at irregular angular positions around the patch perimeter. This pattern is characteristic of very high-order circular modes where multiple simultaneous resonances contribute to the observed return loss minimum, and

suggests a travelling-wave mode behaviour that explains the broad angular spread of the radiation pattern at this frequency.

6. Comparison with Published Literature

Table 3 compares the proposed antenna with representative recently published multi-band antenna designs. The comparison evaluates substrate material, physical size, resonance frequency coverage, and number of simultaneously supported bands.

Table 3 reveals that the proposed design is the only FR4-based entry achieving simultaneous four-band coverage from 5.5 GHz through 34.6 GHz, a 6.3:1 frequency ratio. The single-band Ka-band entries of references [4] and [10] confirm that extending coverage to four simultaneous bands on a low-cost substrate has not been previously demonstrated in the compared literature. The multi-band entries in references [2], [5], and [6] remain below 7 GHz and use physically larger apertures. A further distinguishing feature of the

to 2.5 GHz at 34.6 GHz, which benefits wideband communication systems requiring stable impedance matching across multiple operating bands requiring stable impedance matching across an appreciable instantaneous bandwidth at each operating frequency.

7. Conclusions

This paper has presented the design and comprehensive simulation analysis of a CPW-fed circular patch antenna with strip-line feed, modelled on FR4 substrate and achieving four-band resonance at 5.5 GHz (C-band), 16.7 GHz (Ku-band), 26.3 GHz (Ka-band / 5G mmWave), and 34.6 GHz (Ka-band). The following key conclusions are drawn:

- The proposed configuration (strip on left, left semi-circular ground slot, FR4 at 1.6 mm) achieves four resonance bands with bandwidths of 1.2, 1.7, 2.0, and

2.5 GHz, covering frequency bands associated with C-band, Ku-band, and Ka-

Table 3. Comparison of proposed antenna with recently published multi-band designs

Ref.	Radiator Shape / Structure	Substrate	Size (mm ²)	Resonance Frequencies	Bands	Application
[1]	Slot Antenna	FR4 (4.3)	20×30	3.6 GHz	1	5G sub-6 GHz
[2]	MIMO	FR4 (4.3)	150×70	3.5, 5.0 GHz	2	5G MIMO
[3]	Microstrip Patch	FR4 (4.3)	27×26	4.29, 77 GHz	2	5G/6G
[4]	Reconfigurable mmWave	RT/Duroid	30×23	27 GHz	1	5G mmWave
[5]	Cactus-Shaped	FR4 (4.3)	21×29	3.5, 4.8, 5.8 GHz	3	5G/WLAN
[6]	Two-Port MIMO	RT/Duroid	56.4×36.6	3.4, 4.9, 6.98 GHz	3	5G/6G MIMO
[8]	Slot Antenna	FR4 (4.3)	30×30	4.9 GHz	1	5G sub-6 GHz
[10]	Multi-Slotted	RT/Duroid	53×20	28 GHz	1	5G mmWave
Proposed	Circular Patch	FR4 (4.3)	20×20	5.5, 16.7, 26.3, 34.6 GHz	4	C, Ku, Ka-Band

proposed design is the progressive bandwidth growth from 1.2 GHz at 5.5 GHz

band wireless communication systems.

- The parametric substrate study confirms that Rogers RT ($\epsilon_r = 2.2$) provides the widest Ka-band bandwidth while FR4 offers the best overall cost-performance trade-off for the proposed design.
- The strip-on-left configuration achieves the strongest Ku-band resonance depth (approximately -53 dB at 16.7 GHz) and consistent four-band S11 performance, outperforming the centre-strip baseline. The simulated peak gain values are 7.0 dBi, -0.6 dBi, 1.7 dBi, and 0.5 dBi at the four operating bands, respectively. Furthermore, VSWR values remain below 1.17 across all operating frequencies, satisfying the $VSWR \leq 2$ acceptance criterion and confirming good impedance matching.
- The left-edge semi-circular ground slot produces the deepest Ka-band resonance (approximately -52 dB near 25.5 GHz) and is selected for the optimised design.
- Radiation pattern analysis confirms broadside radiation at 5.5 GHz, higher-order multi-lobe distributions at 16.7 GHz, and progressively complex distributed patterns at the Ka-band frequencies, with spatial complexity increasing with frequency as expected for an electrically larger aperture.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

The data that support the findings of this study are available upon reasonable request from the corresponding author.

Author Contribution Statement

Ujjwal Raghav: Conceptualization, Methodology, Formal analysis, Resources, Data curation, Writing — original draft, Writing — review & editing, Visualization. Kaushal Kumar: Software, Simulation, Validation, Investigation. Manish Kumar, Sandeep Kumar Singh: Supervision, Project administration, Writing — review & editing.

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