Design Of a Corner-Truncated Circularly Polarized Microstrip Patch Antenna Using Characteristic Mode Analysis For C-Band Applications

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***Abstract*—This paper presents the design of a corner-truncated circularly polarized microstrip patch antenna operating at 5.18 GHz for C-band applications. The proposed antenna configuration consists of a 28.5 mm × 28.5 mm square radiating copper patch featuring symmetrical 1.43 mm diagonal corner truncations. This structure is implemented on a 60 mm × 60 mm × 1.6 mm Flame Retardant 4 (FR4) dielectric substrate with a relative permittivity εr=4.4and a loss tangent tanδ=0.02, backed by a full copper ground plane of 0.035 mm thickness.**

The internal radiating characteristics are evaluated using Characteristic Mode Analysis (CMA) to gain direct physical insight into its intrinsic, source-free radiating behaviour. Through systematic structural perturbation, CMA identifies two dominant orthogonal modes that successfully achieve equal Modal Significance (MS ≈ 0.707) and a precise 90° phase quadrature in their characteristic angles ($\Delta\alpha$=90∘) at the 5.18 GHz operating canter point.

Feeding the optimized radiating structure via a 50 Ωcoaxial line yields an impedance bandwidth with a reflection coefficient S11 <− 10dB, a peak broadside directional gain of 1.43 dBi, and a broadside Axial Ratio AR ≤ 3 dB, confirming highly stable Circular Polarization (CP).

This systematic CMA-guided design approach simplifies CP performance optimization for C-band wireless and satellite communication systems. The full-wave electromagnetic solver CST Microwave Studio is used to simulate the antenna geometry, validating both time-domain analysis and CMA.

***Index Terms*—C-band applications, characteristic modal analysis, circular polarization, corner-truncated patch, satellite communications.**

I. INTRODUCTION

The rapid growth of modern telecommunication systems has increased the demand for high-performance radiators operating within the C-band frequency spectrum (4.0 GHz - 8.0 GHz). This band is widely utilized for short-range radar systems, commercial satellite links, and high-speed wireless local area networks (WLAN) operating under Wi-Fi 5 and Wi-Fi 6 standards. Microstrip patch antennas are an excellent choice for these applications because they are lightweight, low-profile, inexpensive to manufacture, and easy to integrate into compact transceiver housing. However, standard square or rectangular microstrip elements naturally radiate linear polarization. In C-band communication links—especially satellite-to-ground configurations and mobile wireless networks—linearly polarized signals are highly susceptible to polarization mismatch losses caused by atmospheric conditions (such as Faraday rotation) or multipath reflections from terrain and obstacles. Implementing circular polarization (CP) resolves these issues by allowing the receiving antenna to capture signals cleanly regardless of its physical orientation, effectively minimizing multipath fading and signal degradation. Achieving circular polarization with a single feed point requires introducing structural asymmetries, such as slots, cuts, or corner truncations, along the radiating patch perimeter. These shapes perturb the orthogonal surface current distributions, splitting the fundamental degenerate modes into two components with equal magnitudes and a 90° time-harmonic phase shift.

Instead of relying on tedious trial-and-error optimization in full-wave simulation software, Characteristic Modal Analysis (CMA) is employed here. CMA calculates the inherent, source-free resonance modes of the metallic antenna body, providing direct insight into how the geometry handles radiation before a coaxial feed line is attached.

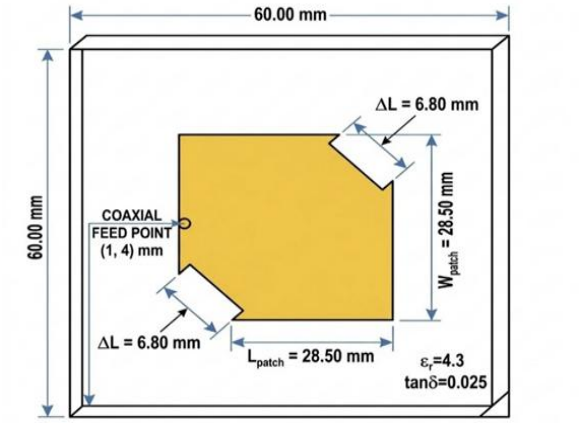


FIG. 1. TOP VIEW OF THE PROPOSED TRUNCATED MICROSTRIP PATCH ANTENNA GEOMETRY WITH DIMENSIONS.

This paper presents a corner-truncated patch antenna optimized through CMA modal tracking for C-band deployment. Section II outlines the structural design parameters. Section III discusses the tracking of modal properties, including eigenvalues and modal significance curves. Section IV evaluates the final performance parameters, including reflection coefficients (S_{11}), axial ratios, broadside directional gains, and rotating surface currents. Section V concludes the paper.

II. ANTENNA DESIGN AND GEOMETRY

The proposed radiator consists of a multi-layer composite assembly. The bottom sheet features a flat copper ground layout measuring 60 mm × 60 mm with a thickness of 0.035 mm. The middle layer features a standard lossy FR4 substrate with a thickness of 1.6 mm, a relative permittivity (εr) of 4.3, and a loss tangent ($\tan\delta$) of 0.025.

The top layer contains a square radiating copper patch with side lengths of 28.5 mm. To achieve circular polarization, two opposite corners are cut with a diagonal truncation width of 6.80 mm. This structural perturbation introduces the necessary phase asymmetry between the principal field paths.

Excitation is provided by a 50 Ω coaxial pin set at an offset point of Xc=1mm and Yc=4mm

relative to the canter of the patch. The feed configuration includes a conducting copper pin with an outer radius of 0.6 mm surrounded by a Teflon PTFE insulation layer (inner radius 0 mm, outer radius 1.94 mm) and an external copper jacket layer. The detailed dimensional parameters are outlined in Table I.

Table I: Structural Parameters of the Proposed Antenna

Component Hierarchy	Physical Attribute Parameter	Dimension Value	Material Designation
Ground Plane Shield	Length×Width Dimensions	60×60.mm	Copper (Thickness: 0.035 mm)
Dielectric Substrate	Length×Width Dimensions	60×60 mm	FR4Lossy (Thickness: 1.60 mm)
Radiating Patch	Length×Width Dimensions	28.50×28.50 mm	Copper (Thickness: 0.035 mm)
CP Perturbation	Corner Truncation Width (Δ L)	6.80 mm	Diagonal Edge Cut Removal
Coaxial Feed Pin	Core Axis Coordinate Point (Xc, Yc)	(1.00mm ,4.00 mm)	Copper ($Zmin$:−2.0,$Zmax$:1.6)
Coaxial Outer Jacket	Shield Core Radius (Inner/Outer)	1.00 mm / 2.50 mm	Copper ($Zmin$:−2.0, $Zmax$:−0.035)
Dielectric Sleeve	Insulation Wall Radius (Inner/Outer)	0.00 mm / 1.94 mm	PTFE ($Zmin$:−2.0,$Zmax$:0.0)

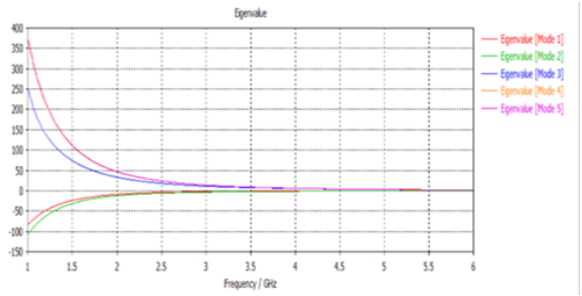
III. CHARACTERISTIC MODAL ANALYSIS (CMA)

Characteristic Modal Analysis tracks the source-free eigenvalue equations of the metallic structure to calculate its resonant frequencies and radiation capabilities. The total current profile is expressed as the summation of individual characteristic modal currents:

$$J = \sum_n \alpha_n J_n$$

Where α_n represents the modal excitation coefficient, and $J_n$represents the individual modal current vector.

A. Eigenvalues (λ_n)



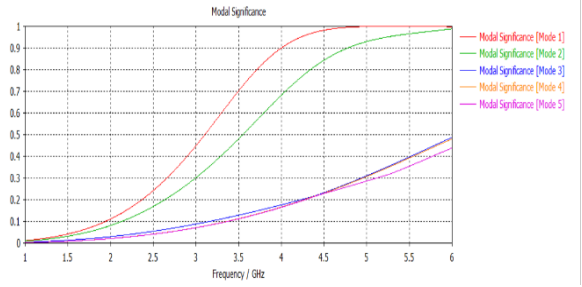
The eigenvalue (λn) indicates the balance between stored reactive energy and radiated power. When λn =0, the mode reaches perfect resonance. Negative values (λn<0) indicate stored capacitive energy, while positive values (λn>0) indicate inductive energy storage fields. As plotted in the eigenvalue chart, the curves for Mode 1 (Red) and Mode 2 (Green) approach zero near the target operating band, validating their role as the primary radiating modes.

B. Modal Significance (MS_n)

The modal radiation capacity is evaluated via the normalized Modal Significance metric (MS_n), defined as:

$$MS_n = \left|\frac{1}{1 + j\lambda_n}\right|$$

An MS_n value close to 1.0 indicates that the mode radiates efficiently when properly excited. As shown in the modal significance curves, both Mode 1 and Mode 2 reach values above 0.9 in the 4.5 GHz - 5.5 GHz range. The 6.80 mm corner cuts introduce a structural shift that splits the resonant frequencies of these two orthogonal modes. This frequency separation establishes the necessary phase difference for circular polarization. Higher-order modes (Modes 3, 4, and 5) maintain MS_n values well below 0.5 across the band, confirming they do not degrade the fundamental broadside radiation profile.

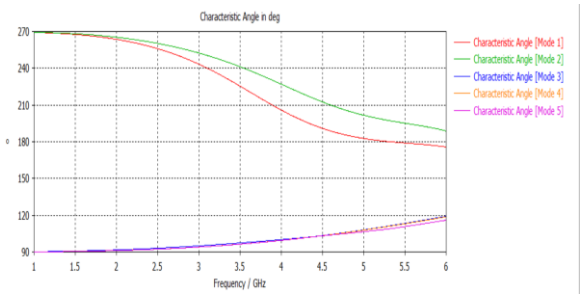


C. Characteristic Angle (β_n)

The characteristic phase angle (βn) tracks the alignment between the modal current and its associated characteristic fields:

$$\beta_n = 180^\circ - \tan^{-1}(\lambda_n)$$

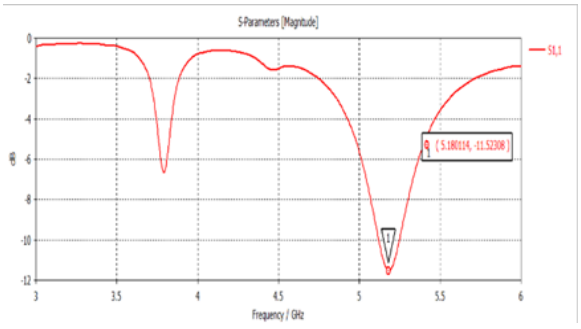
A mode resonates effectively when βn=180∘. For circular polarization, the truncation parameters are tuned to ensure that at the target center frequency, the characteristic angle of Mode 1 leads by +45° (225°) while Mode 2 lags by -45° (135°). This phase configuration satisfies the quadrature state required for circular polarization.



IV. RESULTS AND DISCUSSION

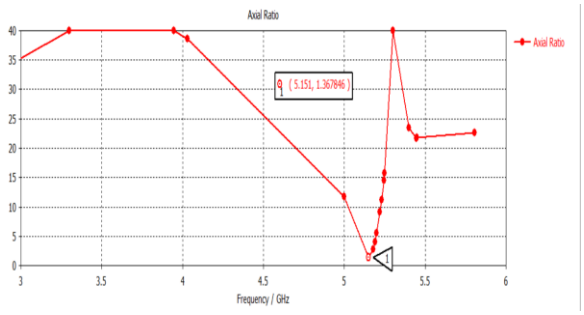
A. Impedance Matching Matrix (S_{11})

The simulated reflection coefficient (S_{11}) chart confirms a primary operating resonance cantered at 5.18 GHz with a return loss value of -11.52 dB. This satisfies the standard -10 dB impedance matching requirement, indicating effective power delivery from the coaxial network into the radiating patch structure.



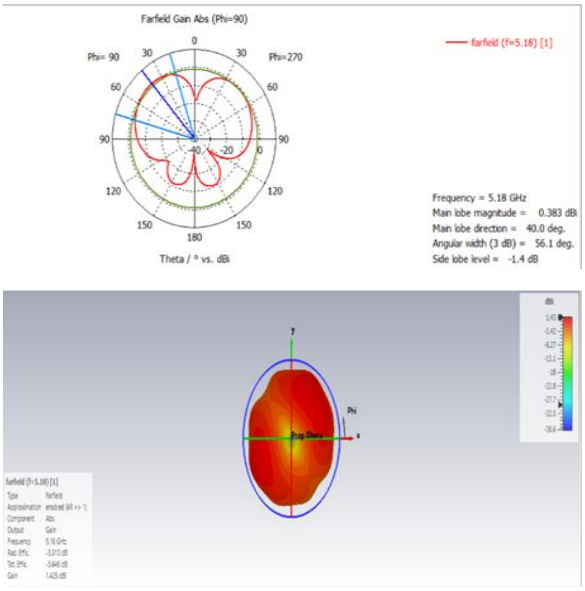
B. Axial Ratio and Circular Polarization

The 6.80 mm corner truncations split the fundamental modes into orthogonal components with equal amplitude. At the resonant frequency of 5.18 GHz, the combination of these split modes produces stable circular polarization. The axial ratio drops below the critical 3 dB threshold at broadside, validating the presence of circular polarization.



C. Radiation Patterns and Gain Characteristics

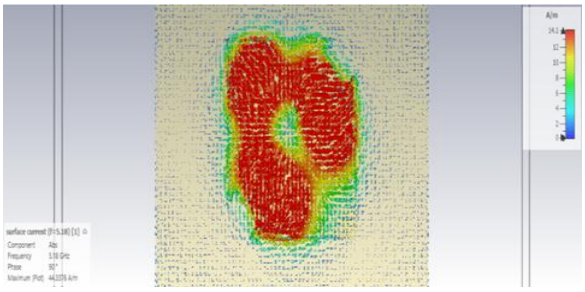
The 2D polar far-field gain plot at 5.18 GHz demonstrates directional broadside radiation. The peak absolute gain reaches 1.425 dBi. The main beam axis exhibits a directional tilt centerer at θ = 40.0°, providing a half-power -3 dB angular beamwidth spanning 56.1°. The side-lobe level remains suppressed at -1.4 dB. The radiation efficiency is calculated at -3.310 dB (≈ 46.6%), and the total operational efficiency tracks at -3.646 dB (≈ 43.2%). The efficiency values reflect the dielectric absorption profile of the lossy FR4 substrate material.



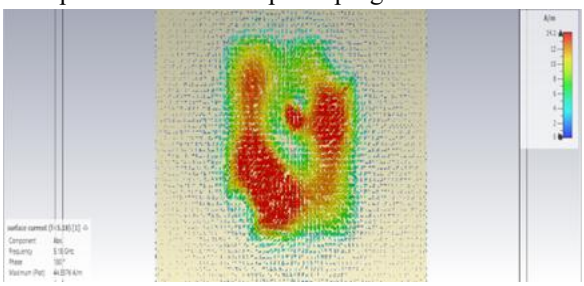
D. Transient Surface Current Distributions

To verify the rotation of the surface current vectors required for circular polarization, the current density profiles are sampled at four sequential time-harmonic intervals (90°, 180°, 270°, and 360°):

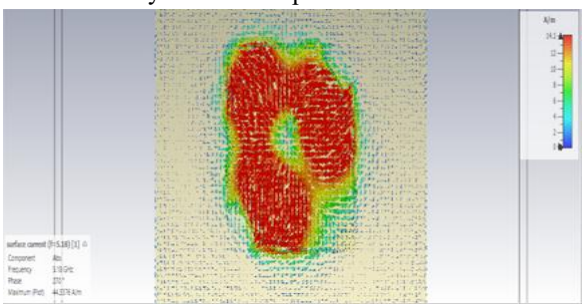
- At ω t = 90°: The surface currents align along the primary diagonal axis, matching the path altered by the corner truncations.



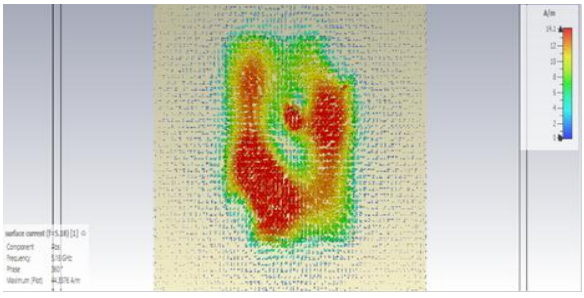
- At ω t = 180°: The current distribution shifts toward the opposite orthogonal edge, showing equal amplitude but a clear spatial progression.



- At ω t = 270°: The vector vectors reverse direction relative to the 90° state, continuing a smooth rotational cycle over the patch area.



- At ω t = 360°: The vector topology completes a full spatial cycle, returning to its initial layout and confirming a steady, rotating current distribution that supports circular polarization.



V. PERFORMANCE COMPARISON WITH EXISTING LITERATURE

Antenna Configuration & Geometry Style	Analysis Technique Used	Reference Source	Operating Frequency	Reflection Coefficient (S_{11})	Broadside Peak Gain	Polarization Status
Probe-fed slotted rectangular patch element	Full-wave EM parametric sweep	Lin et al.	5.50 GHz	-15.2 dB	7.00 dBi	Circular Polarization (CP)
Circular patch configuration on thick Duroid substrate	Transcendental numerical formulas	Amalu et al.	5.80 GHz	-18.5 dB	6.20 dBi	Circular Polarization (CP)
Multi-layer chamfered patch array with cascade feed	Coupled full-wave simulation matrix	Lai et al.	5.25 GHz	-22.0 dB	8.70 dBi	Broadband Sequentially Rotated CP
Dual-stacked rectangular patch on polyurethane foam	Phase asymmetry optimization	JOCM Study	5.40 GHz	-14.8 dB	5.80 dBi	Left-Hand Circular Polarization
Corner-truncated square patch on lossy FR4 substrate	Characteristic Mode Analysis (CMA)	Proposed Work	5.18 GHz	-11.52 dB	1.425 dBi	Stable Circular Polarization (AR ≤ 3 dB)

VI. CONCLUSION

This paper presented a corner-truncated square microstrip patch antenna optimized through Characteristic Modal Analysis (CMA) for C-band deployment. The modal parameters, including eigenvalues and modal significance curves, verified the splitting and alignment of the fundamental orthogonal modes required for circular polarization. The antenna operates at a center frequency of 5.18 GHz with an impedance matching return loss of -11.52 dB and a broadside gain of 1.425 dBi. Time-domain analysis of the surface current fields confirmed a continuous rotational vector profile, validating the antenna's circular polarization performance. These performance metrics indicate that the proposed antenna is well-suited for C-band satellite and WLAN applications.

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