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The design of a multi-band antenna with improved higher-order mode radiation using characteristic mode analysis for L5-band, L1-band, and S-band applications

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Keywords

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L5-band;
Orthogonal modes;
S-band;
Tri-band antenna.

Abstract

A novel multi-band antenna with an improved higher-order mode radiation pattern based on Characteristic Mode Analysis (CMA) is presented. The tri-band characteristic is achieved by exciting one higher-order mode and two orthogonal modes. The initial orthogonal mode is achieved by converting the antenna from a circular to an elliptical shape. Surface current reshaping transforms the higher-order conical radiation pattern mode into a broadside direction. The surface current nulls with out-of-phase are moved toward the patch corners using CMA. Characteristic modes are excited with a coaxial feed, which uses full-wave Electromagnetic (EM) simulation. It excites two orthogonal modes at 1176 MHz and 1575 MHz for L5-band and L1-band applications, respectively, and one higher-order mode at 2500 MHz for S-band applications. The proposed antenna has moderate gain and broadside radiation patterns across the operational frequency bands. The working of the antenna and validation are represented by equivalent circuit modeling. The experimental results present excellent agreement with EM simulated results.

1. Introduction

Space communication and radar applications require multi-band antennas with broadside radiation characteristics for better signal coverage. Microstrip antennas are frequently used in multi-band applications with appealing abilities, including their low price, low profile, less heaviness, and effortlessness of circuit integration [1,2]. Multi-band antennas are commonly designed using stacked multi-resonators, slots, and planar inverted antennas. The multi-resonators in a stacked antenna enhance the lateral dimension or height. The methods used, such as shorting pins, etched slots, and adding extra parasitic components, are responsible for distorted radiation patterns and high cross-polarization [3,4].

The higher-order modes are the best solution for a multi-band and thin-profile antenna. The fundamental mode is radiated in a broadside direction, but higher-order mode radiation patterns cannot maintain a broadside direction and have high E-plane side lobes [5]. Therefore, we require proper methods to convert higher-order mode radiation patterns in the broadside direction for multi-band applications.

The three methods are discussed in Ref. [2] to convert higher-order mode radiation patterns in broadside and minimize E-plane side lobes. The first method is to partially load meta-material in patches to change the conical to the broadside radiation pattern. However, in these methods, the antenna's fabrication complexity is high. The second method is adding reflectors to the antenna structure. This method also increases antenna volume and is unreliable for integration with planar circuits. In the third method, there are controlling field distributions in the antenna structure with higher-order modes to maintain broadside radiation patterns. Some literature is available based on a third method, such as inserting a non-resonant slot at the patch center to diminish the E-plane side lobes of TM_{12} mode [6-8]. The higher-order

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radiation pattern of the patch is transformed into the broadside direction using a differential feed with the etched center slot of the patch discussed in [1,4]. In the equivalent magnetic current, magnitudes are controlled to convert the higher-order mode from a conical to a broadside radiation pattern by utilizing port feeding along with shorting pins and slots [2]. However, these techniques enhance circuit complexity by loading slots and pins with differential feeding. So, to overcome the antenna's complexity and radiation characteristics of higher-order modes, the antenna structure is modified [9-20]. The broadside radiation pattern is obtained by shifting out-of-phase surface current nulls toward the patch corners. This paper presents a new technique for refining the antenna radiation pattern of the higher-order mode from conical to broadside. The three-band characteristics are accomplished by reallocating one higher-order mode (TM_{12}) at the S-band and two orthogonal modes (TM_{11H}, TM_{11V}) at the L5-band and L1-band by using re-shaping of the circular patch antenna. The mode analysis method provides the structurally dependent modes.

2. Design considerations of tri-band antenna

2.1. Cavity model method based modal analysis

Cavity Model Method (CMM) is an analytical method for understanding conventional microstrip antenna characteristics with vital assumptions. But it is hard to comprehend irregular-shaped microstrip antennas. The circular cavity model exhibits some resonance modes. For TM^{Z}_{mno} mode, the resonance frequency is given as:

$$\left(f_r\right)_{mn0} = \frac{c}{2\pi\sqrt{\varepsilon_r}}\left(\frac{\chi'_{mn}}{R}\right), \tag{1}$$

where R denotes the circular patch radius shown in Figure 1, c is the free space light speed, ε_r is the relative permittivity of the substrate and χ'_{mn} determines the resonant frequency order. At $\chi'_{11} = 1.8412$ for the first-order mode (TM^{Z}_{110}) and $\chi'_{12} = 3.0542$ for the second-order mode (TM^{Z}_{120}).

Eq. (1) can be used to calculate the R parameter of a circular patch antenna. The proposed antenna is designed with an *FR-4* substrate with $\varepsilon_r = 4.3$ and $\tan\delta = 0.025$. Its lower frequency for the first-order mode is 1176 MHz (TM^{Z}_{110}). The parameter is calculated as given below:

$$R = \frac{1.8412 * 3 * 10^8}{2\pi * 1176.45 * 10^6 \sqrt{4.3}} = 36.05\,\text{mm}.$$

By using R and Eq. (1), we can calculate the second-order mode TM^{Z}_{120} frequency as:

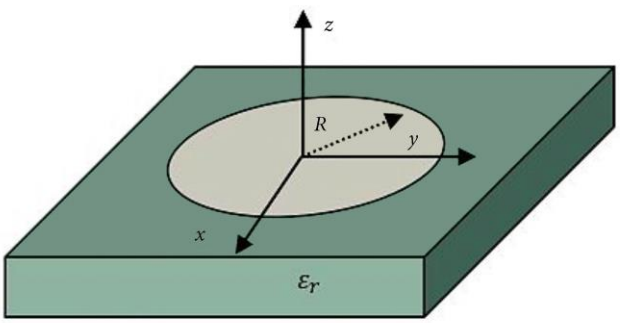


Figure 1. Dielectric-loaded circular patch antenna.

$$\left(f_r\right)_{120} = \frac{3.0542 * 3 * 10^8}{2\pi * 36.05 * 10^{-3}\sqrt{4.3}} = 1951.72\,\text{MHz}.$$

2.2. Antenna re-shaping using CMA

2.2.1. Brief introduction of CMA theory

The usual mode analysis method is widely utilized in microwave circuit design. It provides step-by-step systematic design analysis and in-depth physical mode behavior in conducting structures. The Characteristic Mode Analysis (CMA) is based on the Method of Moments (MoM), and characteristic modes can be numerically calculated for any arbitrary shape of a conducting structure [21-26]. The following factors are required for performing modal analysis of conducting systems.

Eigenvalue λ_n: The Eigenvalue for the nth mode denotes the ratio of near-structure energy storage $P_{reac,n}$ to radiated energy $P_{rad,n}$ [27]:

$$\lambda_n = \frac{< J_n^* X\left(J_n\right) >}{< J_n^* R(J_n) >} = \frac{P_{reac,n}}{P_{rad,n}}, \tag{2}$$

where J_n^* (* stands for the conjugate operator) is the characteristic current, and R and X are the corresponding impedance matrix's real and imaginary components of the conducting body.

The properties of eigenvalues are given as [28-31]:

(1) $\lambda_n > 0$, mode is inductive and stores magnetic energy;
(2) $\lambda_n < 0$, mode is capacitive and stores electric energy;
(3) $\lambda_n = 0$, mode is in resonance.

Modal Significance (*MS_n*): MS_n is another crucial parameter for representing the mode's radiation characteristics. It is defined as [32]:

$$MS = \left|\frac{1}{1 + j\lambda_n}\right|. \tag{3}$$

When $MS_n > \frac{1}{\sqrt{2}}$, then it is significant for the radiating mode and vice versa.

The coupling behavior of the nth characteristic mode and excitation (feed excitation) is represented as input admittance (Y_{in}) with current (I_{in}) and voltage (V_{in}) at the feed location [33]:

$$Y_{in} = \frac{I_{in}}{V_{in}} = \sum \frac{\left(J_n^p\right)^2}{1 + j\lambda_n}, \tag{4}$$

where J_n^p is the nth characteristic mode current, Γ_n is the corresponding modal reflection coefficient (Eq. (5)), and the antenna is excited by a feed with characteristic impedance Z_0.

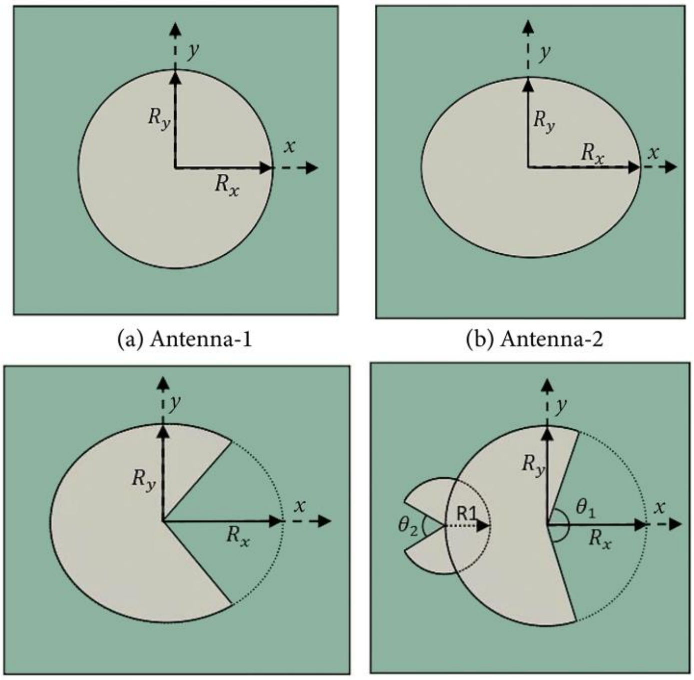
$$\Gamma_n = \frac{\left(\frac{1}{Y_{in}^n}\right) - Z_0}{\left(\frac{1}{Y_{in}^n}\right) + Z_0}. \tag{5}$$

2.2.2. Antenna-1 modal analysis with parametric study

The working principle of a tri-band antenna with higher-order mode radiation characteristic enhancement is demonstrated by surface current distribution and radiation pattern analysis using the CMA method. The design and simulation are carried out using the CST studio Electromagnetic (EM) tool.

In this step, the initial circular patch antenna is designed using a calculated parameter R=36.05 mm through the CMM, as shown in Figure 2(a). Figure 3(a) depicts the MS_n values plot for four modes of Antenna-1 with distinct values of R (34.50 mm, 35.5 mm, and 36.50 mm). In this plot, modes 1, 2, and 4 are resonant because their MS_n values are more significant than $MS_n > \frac{1}{\sqrt{2}}$. Mode-3 is not resonant, and it stores magnetic energy due to $\lambda_3 > 0$, while λ_1 (for mode-1), λ_2 (for mode-2) are zero at 1176 MHz, and λ_4 (for mode-4) is zero at 2004 MHz as in depicted Figure 3(b).

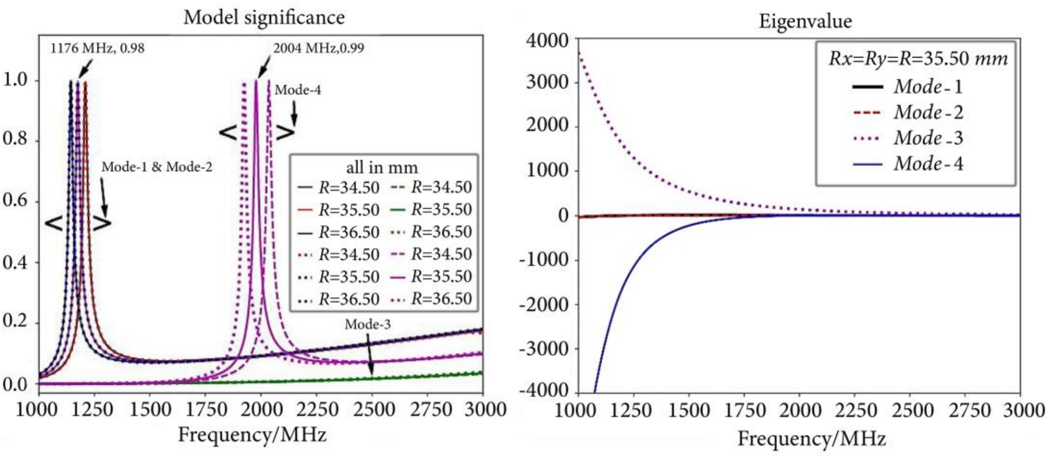
Modes 1 and 2 are orthogonal (TM_{11H} & TM_{11V}) and overlap at the same frequency, but mode-4 is a higher-order mode (TM_{12}). At R=35.50 mm, the antenna is resonant at 1176 MHz (due to TM_{11H} & TM_{11V}) and 2004 MHz (due to TM_{12}). The working mechanism of Antenna-1 can be intuitively understood by looking at the surface current and the radiation pattern, as revealed in Figure 4(a)-(d) and Figure 5(a)-(d), respectively. Mode-1 and mode-2 have orthogonal radiation patterns to each other because the arrows of the surface currents are 90° shifted relative to each other. The broadside radiation pattern of each mode is due to the arrows of surface currents being distributed in phase. Mode-3 behaves inductively owing to its arrows of surface currents being in a closed loop, which is verified by the eigenvalue plot in Figure 3(b). The radiation pattern of mode-4 is a conical shape owing to the surface out-of-phase current arrows at the middle of the patch. Figure 3 illustrates a detailed analysis centered on Antenna-1, with the primary goal of extracting the modal properties associated with specific circular patch dimensions. The analysis was conducted without any excitation, and it covered up to four different modes for Antenna-1. These results were obtained using the CST Studio's CMA analysis software tool.



(a) Antenna-1 (b) Antenna-2

(c) Antenna-3 (d) Antenna-4

Figure 2. Proposed antenna design steps geometries.



(a) Antenna-1 parametric study MS plot (b) Eigen value plot

Figure 3. Antenna-1 modal analysis.

2.2.3. Antenna-2 modal analysis with parametric study

The circular patch antenna is transformed into an elliptical shape using parametric analysis, as shown in Figure 2(b). The orthogonal modes were separated by parametric study at 1176 MHz and 1575 MHz (L1-band) with R_x = 35.5 mm and R_y = 25.5 mm, and higher-order mode-4 is located at 2150 MHz as in Figure 6. The radiation pattern remains unchanged for modes 1, 2, and 3 due to a similar surface current distribution as discussed in the circular-shaped Antenna-1. Still, the radiation pattern for mode-4 is dramatically changed due to the changing surface current in the elliptical-shaped antenna, as shown in Figure 4(e)-(h) and its corresponding far-field is shown in Figure 5(e)-(h). In this step, the desirable mode-1 at 1176 MHz and mode-2 at 1575 MHz are achieved, and further, the antenna needs to be reshaped for the S-band to achieve tri-band characteristics.

2.2.4. Antenna-3 modal analysis with parametric study

The elliptical-shaped Antenna-2 is reshaped with parameter $\theta 1$, as shown in Figure 2(c). The parametric study with different $\theta 1$ (85°, 95°, and 105°) of Antenna-3 is shown in Figure 7. At $\theta 1$=95°, modes 1, 2, and 4 are resonant (due to $MS_n > \frac{1}{\sqrt{2}}$) for 1176 MHz, 1575 MHz, and 2500 MHz frequency bands, but mode-3 is not resonant (due to MS_n=0), and behaves inductively, storing magnetic energy. This step realizes the tri-band characteristics for L5, L1, and S-band applications, respectively. The orthogonal modes (mode-1, 2) radiation patterns are in the broadside direction due to in-phase surface current distribution. Still, the radiation pattern of mode-4 is not in the broadside direction due to the availability of out-of-phase surface currents nulls in the center, as shown in Figure 4(i)-(l) and the corresponding far-field shown in Figure 5(i)-(l). The mode-4 at 2500 MHz for S-band is not desirable for broadside coverage because of the E-plane show high level of adjacent lobes. This problem can be fixed further by altering the antenna design. So, the corner sides of the antenna construction get surface out-of-phase current nulls.

2.2.5. Antenna-4 modal analysis with parametric study

In this step, the Antenna-3 is further re-shaped with the new parameter $R1$ and $\theta 2$ to convert the broadside radiation pattern of higher-order mode-4 as shown in Figure 2(d). Figure 4 and Figure 5 show parametric study plots of parameters $R1$ and $\theta 2$ with different values. Using surface currents and radiation pattern studies, the new parameters ($R1$& $\theta 2$) are varied. So, the broadside radiation pattern of mode-4 is achieved while maintaining stable desired frequency bands. Figure 8 shows the Antenna-4 modal analysis. At $R1$=11.33 mm and $\theta 2$=72°, the radiation patterns of mode-4 are in a broadside direction. Because there are no out-of-phase surface currents null in the center of the patch

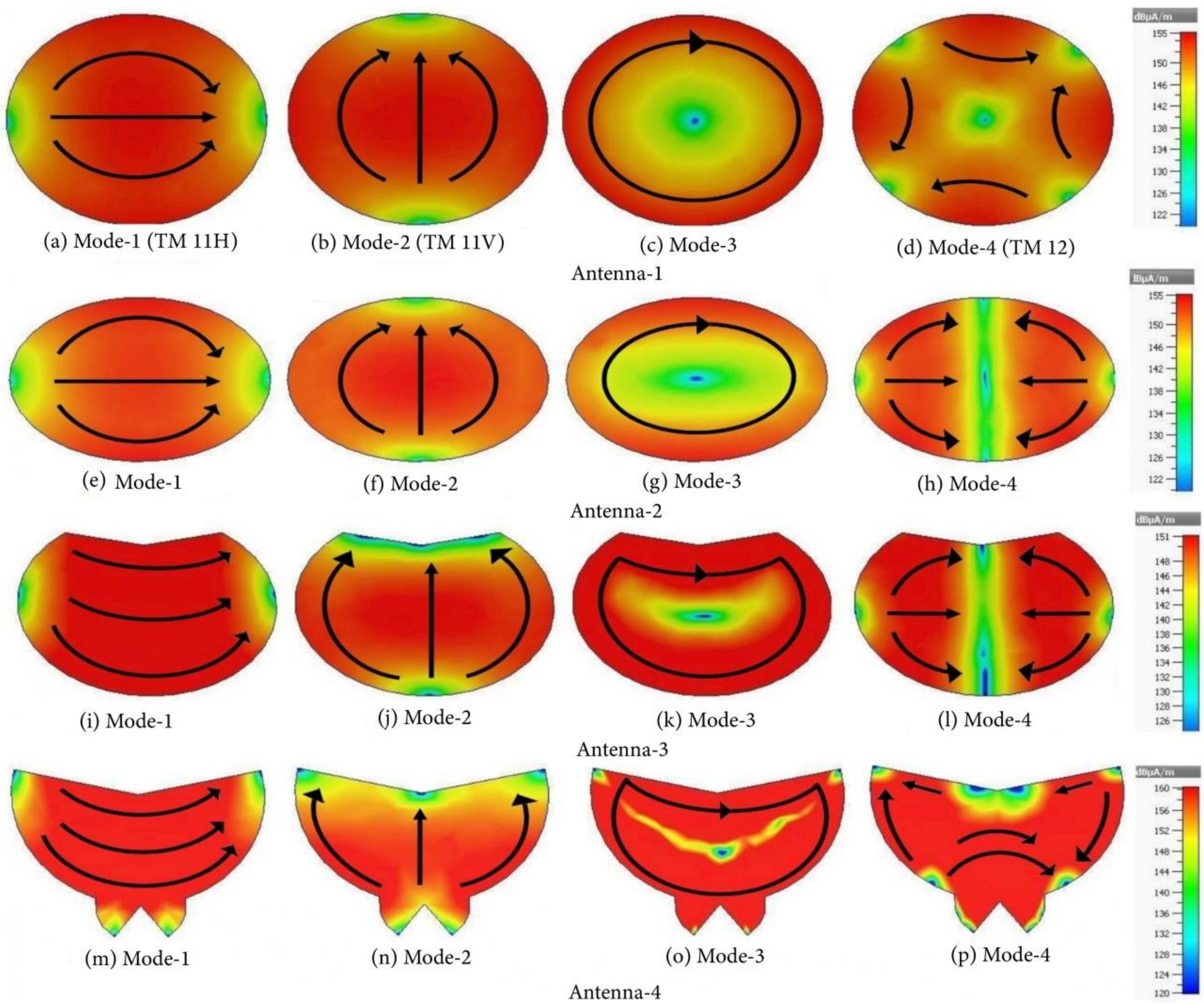


Figure 4. Surface current distribution of antennas.

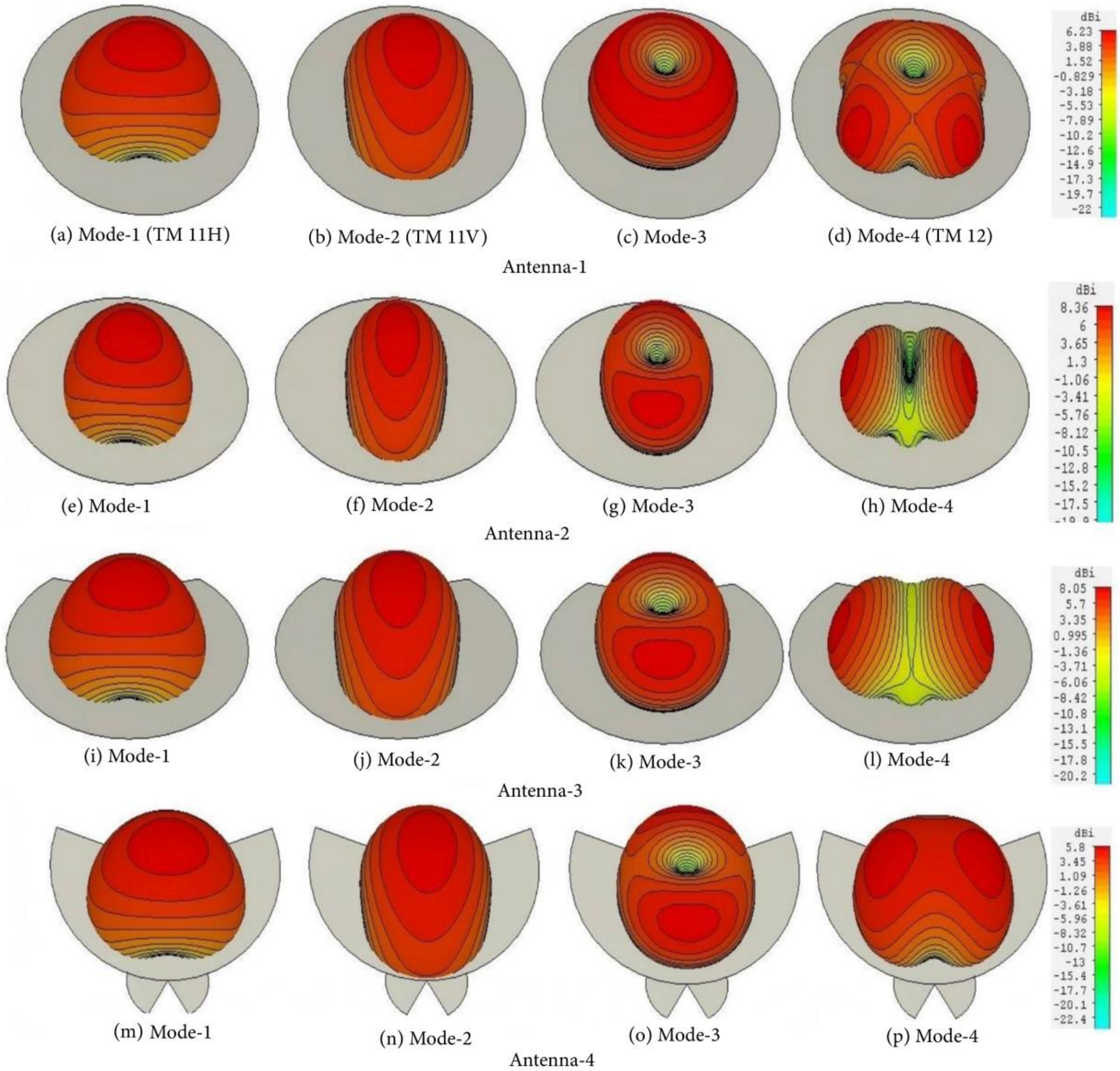


Figure 5. Far-field radiation patterns of antennas.

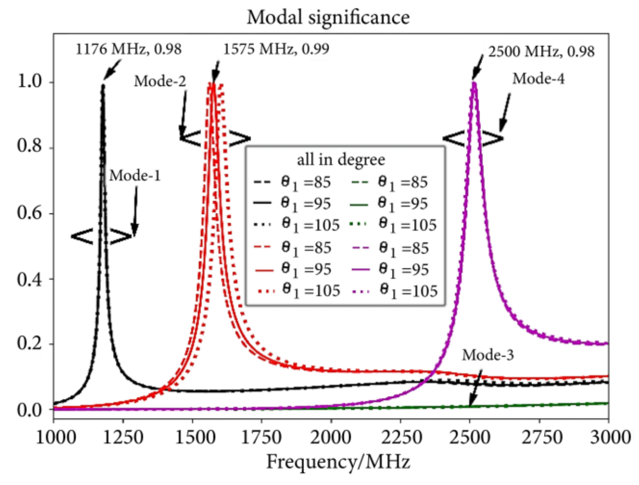


Figure 6. Antenna-2 parametric study MS plot.

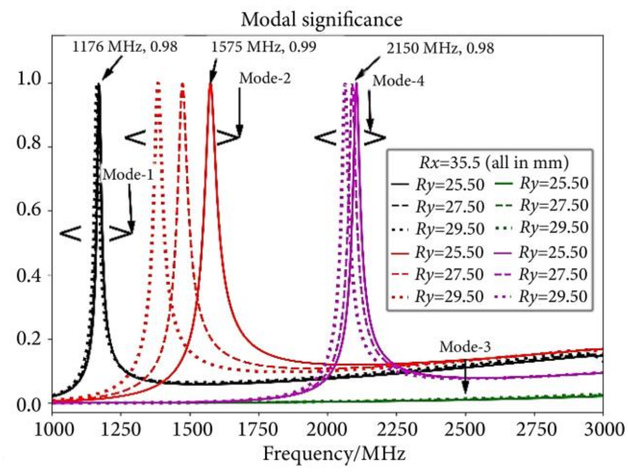
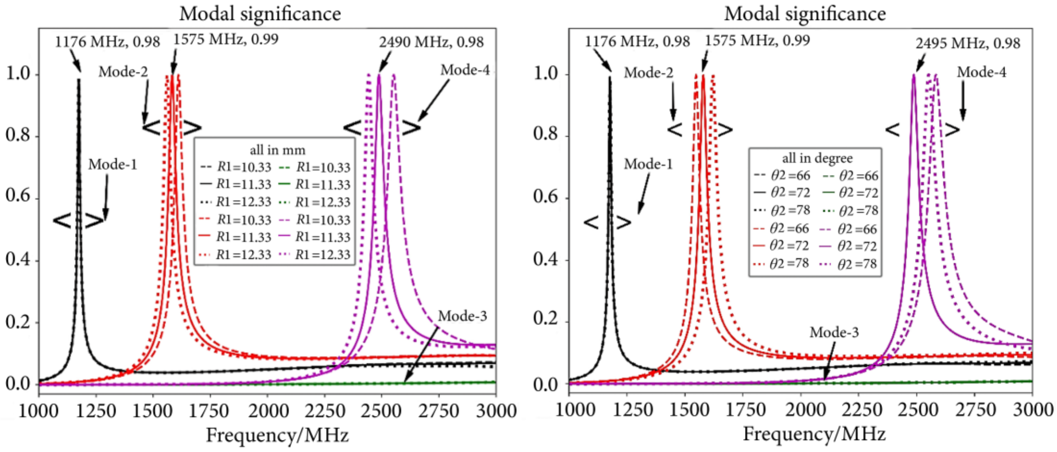


Figure 7. Antenna-3 parametric study MS plot.

are similar for mode-1 and mode-2 in the broadside direction as shown in Figures 7(m)-(p) and 8(m)-(p). The process for converting the broadside radiation pattern of a higher-order mode along with orthogonal modes is well presented in far-field plots with the $\phi = 90°$ and $\phi = 0°$ as represented in Figures 9 and 10.

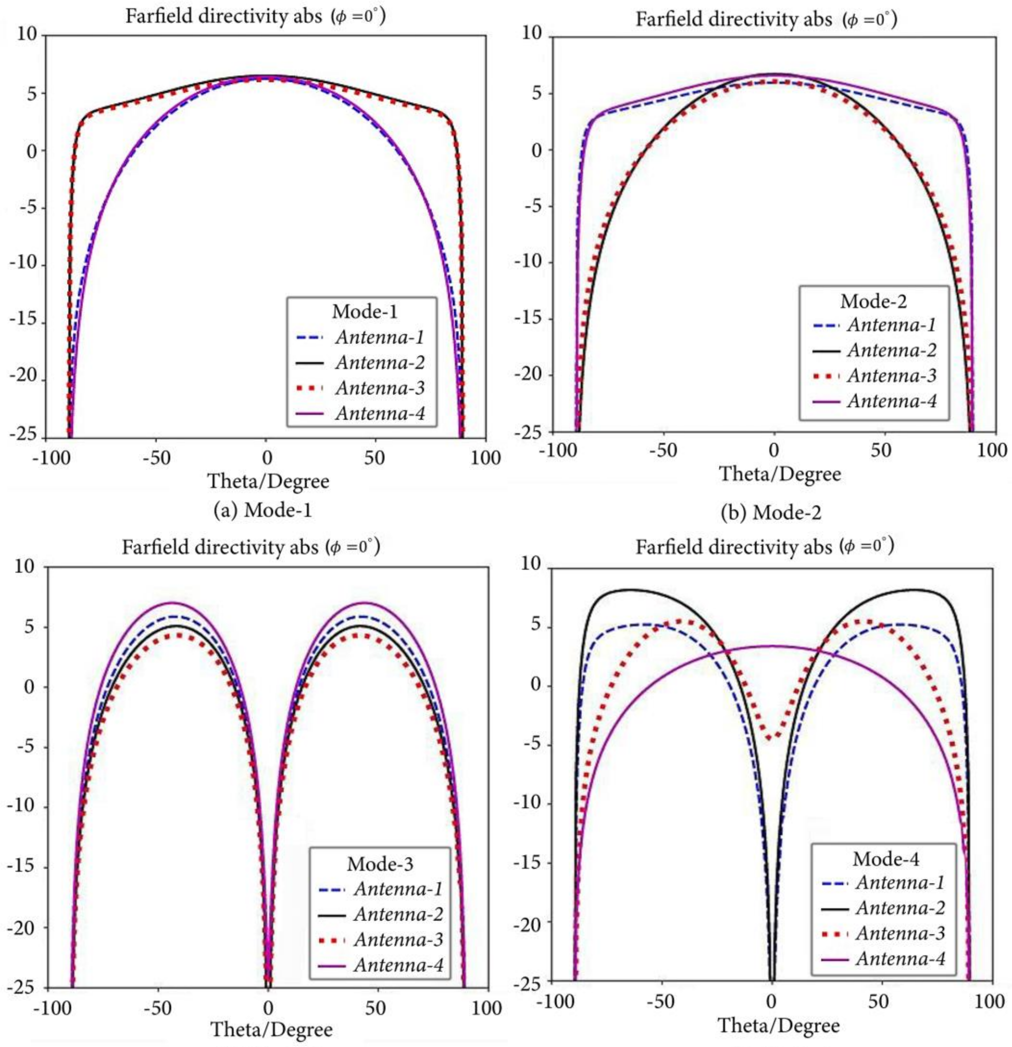
2.3. Tri-band antenna in full-wave with excitation

Figure 11 depicts the optimized tri-band antenna geometry with coaxial feed. The desired characteristic modes are excited by parametric study of coaxial feed location (x_0, y_0) in full-wave FIT simulation, as shown in Figure 12. In this figure, modes 1, 2 and 4 are excited separately and simultaneously



(a) Antenna-4 parametric study MS plot with $R1$ (b) Antenna-4 parametric study MS plot with $\theta 2$

Figure 8. Antenna-4 modal analysis.



(a) Mode-1 (b) Mode-2 (c) Mode-3 (d) Mode-4

Figure 9. Far-field radiation characteristics at $\phi = 0°$.

with different feed locations at x_0=-20.93 mm, y_0=9.33 mm and excited simultaneously at 1179 MHz, 1580 MHz, and 2488 MHz.

2.4. Experimental validation of the proposed antenna

Figure 13 illustrates the fabricated layout of the antenna. The S_{11} parameter of design is tested in an anechoic chamber, and radiation patterns are analyzed using a vector network analyzer, as shown in Figure 14. The S_{11} parameter comparison results between CST EM-tool and measurements by VNA are depicted in Figure 15. Figure 16 illustrates measured peak gain is more than 4.9 dBi in all desired bands. The simulated and measured results have a slight difference due to fabrication tolerance and

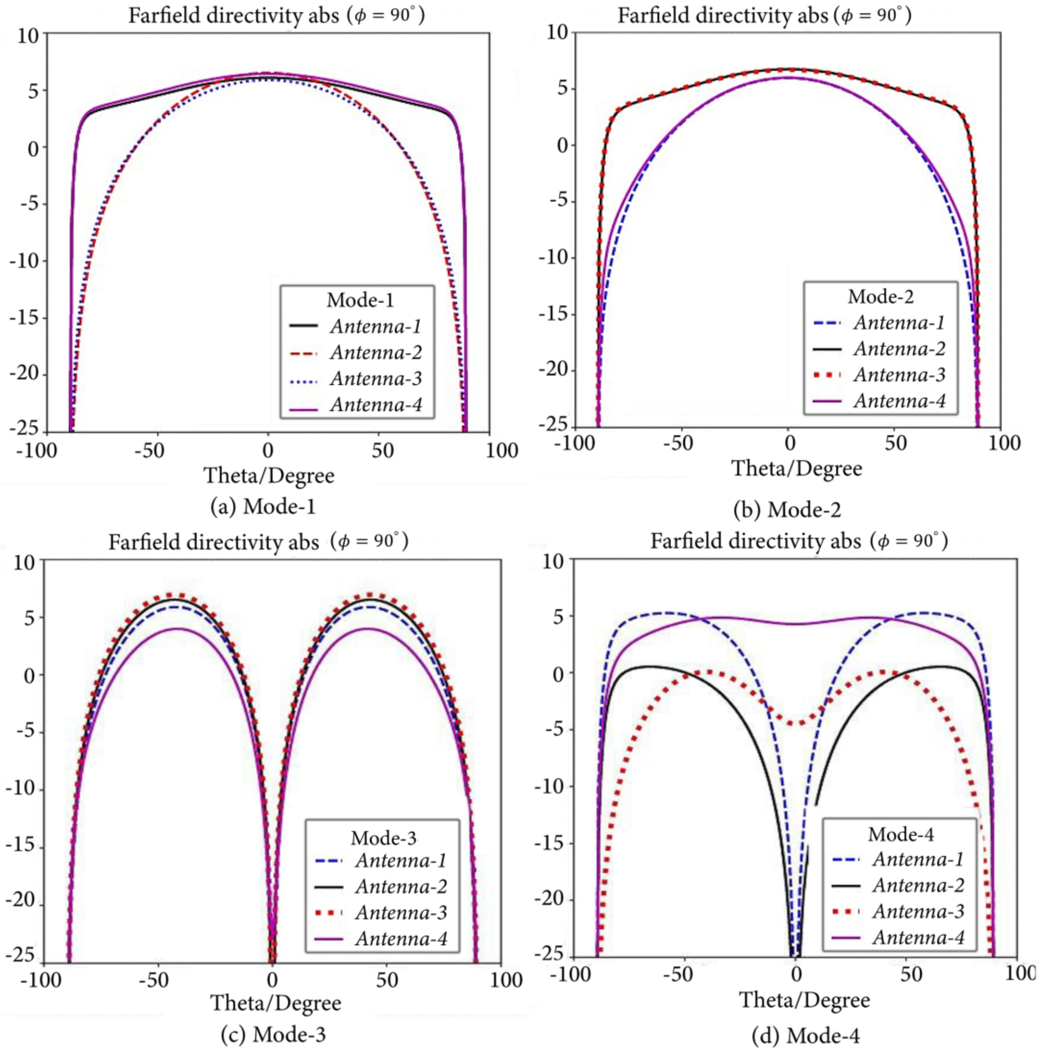


Figure 10. Far-field radiation characteristics at $\phi = 90°$.

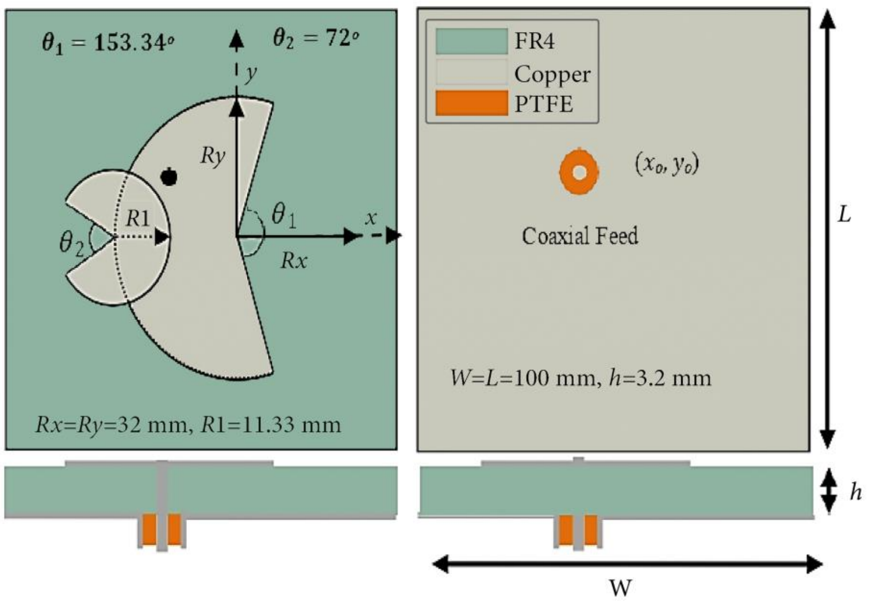


Figure 11. Geometry of proposed tri-band antenna.

measurement error. Figure 17 shows the antenna co-polarization ("solid lines" for simulated and "dash lines" for measurement) and cross-polarization ("dotted lines" for simulated and "dash-dot lines" for measurement) along with measurement results with E ($\phi = 90°$) and H ($\phi = 0°$) plane. The simulated and measured cross-polarization patterns are below -19 dB in the broadside direction for each band. So, the antenna has decent isolation between co- and cross- polarization for all

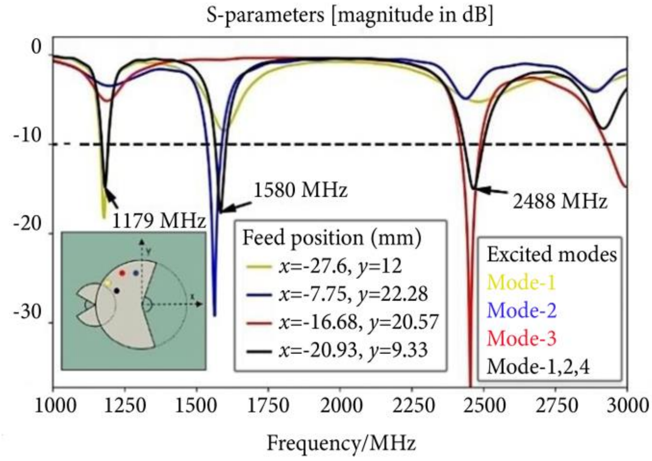


Figure 12. S_{11} plot for modes excitation with feed.

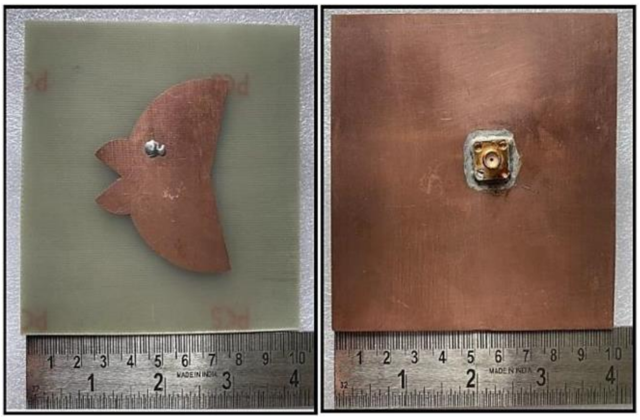


Figure 13. Photograph of the fabricated layout of the proposed tri-band antenna.

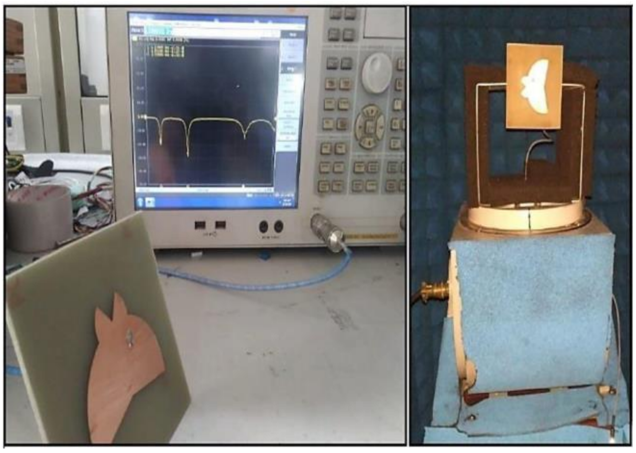


Figure 14. S_{11} and radiation pattern measurement setup of the proposed antenna.

desired bands. With only slight variations resulting from the measuring environment and manufacturing faults, the measurement results are quite similar to those of the simulation.

3. The antenna ECM design

The Equivalent Circuit Modelling (ECM) of the proposed antenna is represented in Figure 18. In this, the tri-band antenna is represented by three parallel Resistor-Inductor-Capacitor (RLC) circuits. Modes 1, 2, and 4 are represented

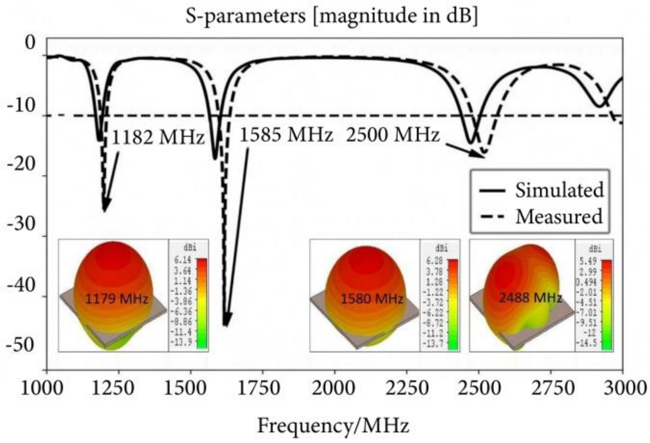


Figure 15. Scattering Parameter (S_{11}) of the antenna.

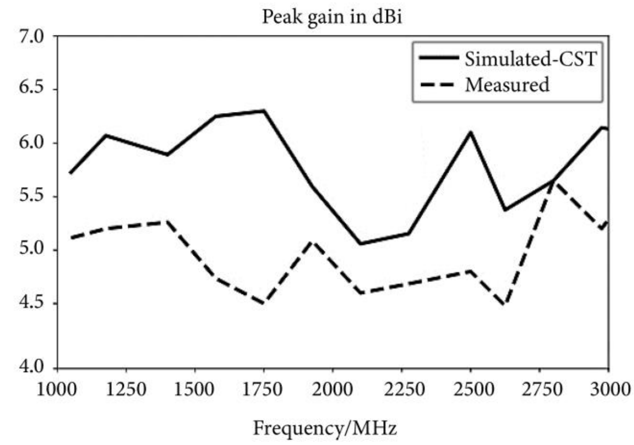
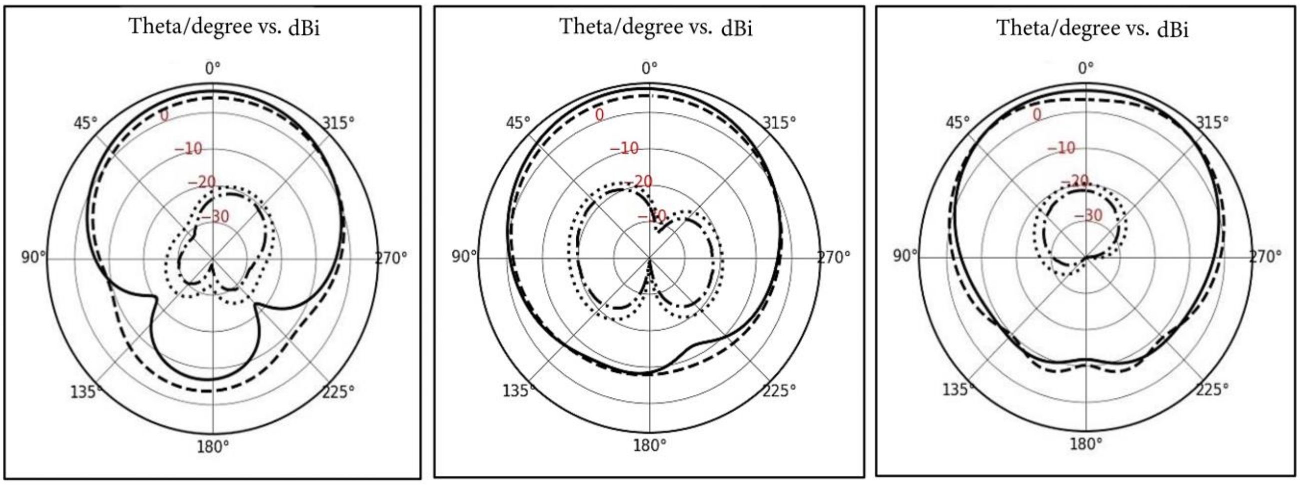


Figure 16. Simulated and measured peak gain.

by R1-L1-C1, R2-L2-C2, and R3-L3-C3, respectively, as shown in Figure 18(a). These modes are triggered by Port 50. The port is coupled to these three RLC circuits through L_0, C_0 coupling, an inductor, and a capacitor. The ECM is simulated in CST circuit simulation, which optimizes the circuit parameters according to the S_{11} characteristic as shown in Figure 18(b). Figure 15 displays the validation of the S_{11} from equivalent circuit simulation with simulated full-wave simulation and measurement results.

4. Analysis of the proposed work concerning the existing work

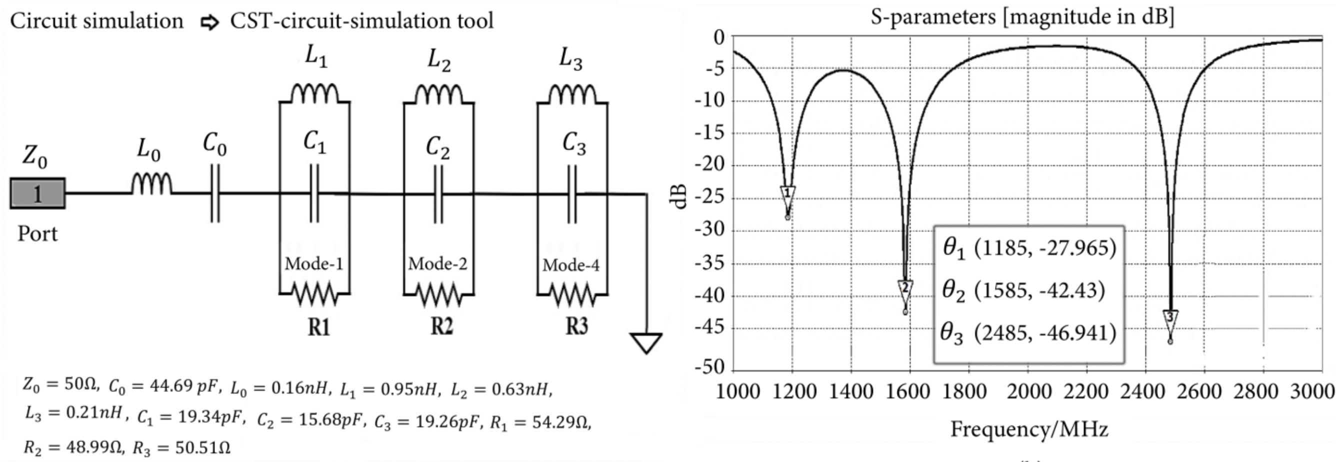
The comparisons with similar work are listed in Table 1. In Ref. [1], short pins and slots are employed to generate the dual-band characteristic, and a narrow slot with a differential feed is used to enhance higher-order modes. A similar method is discussed in [5] for the tri-band antenna with higher-order mode enhancement. The structures' complexity is high in both cases regarding fabrication. The higher-order mode enhancement is achieved by placing a narrow slot at the patch center, as reported in [4,6] for dual- and single-band antenna. The dual-band antenna characteristic is achieved in [2] by exciting TM_{010} and TM_{030} modes, and putting Double-Negative (DNG) or Mu-Negative (MNG) metamaterial is utilized to enhance the higher-order mode radiation pattern. This paper proposes a new approach to improving higher-



(a) $\phi = 90^{\circ}$, 1174 MHz (b) $\phi = 90^{\circ}$, 1575 MHz (c) $\phi = 90^{\circ}$, 2495 MHz

(d) $\phi = 0^{\circ}$, 1174 MHz (e) $\phi = 0^{\circ}$, 1575 MHz (f) $\phi = 0^{\circ}$, 2495 MHz

Figure 17. The proposed antenna's measured and simulation-based radiation pattern {Solid line co-pol (Simulated), dashed line co-pol (Measured), square-dot line cross-pol (Simulated), dash-dot cross line pol (Measured)}.



(a) (b)

Figure 18. (a) ECM analysis; (b) S_{11} of ECM of proposed antenna.

order mode radiation pattern antenna by modifying antenna design. The modified antenna design obtains the surface out-of-phase current nulls toward the patch corners by exciting two orthogonal modes and one higher-order mode for tri-band applications [33-35].

5. Conclusion

In this paper, a new approach is used to design and analyze a tri-band antenna to enhance higher-order mode radiation characteristics using Characteristic Mode Analysis (CMA). The two orthogonal modes at the L5 and L1 bands and one higher-order mode at S-band are reallocated to obtain the tri-band characteristic. The radiation characteristics of the higher-order mode are enhanced by shifting the surface current nulls. It is modifying the antenna structure with out-of-phase nulls toward the patch corners. The designed antenna fabrication complexity is relatively low compared to earlier literature. The slots, shorting pins, or differential feed have not been used in the designed antenna. Only reshaping the antenna structure obtains multi-band antenna characteristics. The final antenna design was fabricated on low-cost *FR-4* material, and the S_{11} parameter and radiation patterns were tested. The measurement results are nearly identical to the Electromagnetic (EM) simulation results. The designed antenna's resonance frequencies are 1182 MHz, 1585 MHz, and 2500 MHz, and it has sufficient gain and a broadside radiation pattern for Global Positioning System (GPS) application in the L1-band and Indian Regional Navigation Satellite System (IRNSS) application in both L5 and S-band.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

First author: Conceptualization; Methodology; Investigation;

Table 1. Comparison of proposed approach with previous work.

Ref.	Multi-band methodology	Enhancement of higher-order mode methodology	Resonant-mode (Frequency MHz)	Volume (mm^3)	Material	Complexity	Peak gain (dBi)
[1]	Adding shorting pins and slots	A narrow slot with differential feed	2 (3600, 5900)	100*100*2	F4B	High	10.2, 10
[2]	Assembling the patch's shorting pins and slots	Differential feeding with shorting pins and slots	3 (3900, 4950, 5900)	110*90*1.58	Rogers 5880	High	10, 10.4, 10.2
[3]	Exciting TM_{010} and TM_{030} modes	Putting a MNG or double-negative metamaterial into operation	2 (903, 1796)	120*150*5	MNG or DNG	High	5.19, 7.47
[5]	Not reported	Narrow slot at the patch center	2 (1800)	330*330*1.54	Not reported	Simple	7
[6]	Not reported	Embedded narrow slot at patch center	1 (1000)	Not reported	Arlon Diclad 527	Simple	13
This work	Excitation of two orthogonal modes and one higher order mode	Surface current nulls (out-of-phase nulls) shifting toward the patch corners by re-shaping the antenna structure	3 (1182, 1585, 2500)	100*100*3.2	*FR-4*	Simple	5.2, 4.6, 4.2

Formal analysis; Data curation; Software; Validation; Visualization; Writing – original draft.

Second author: Conceptualization; Methodology; Supervision; Validation; Writing – review & editing.

Third author: Investigation; Formal analysis; Validation; Writing – review & editing.

Fourth author: Investigation; Validation; Resources; Writing – review & editing.

Fifth author: Supervision; Project administration; Resources; Writing – review & editing.

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