

Compact Swastik-Slot Loaded Circularly Polarized Antenna with Defected Ground Structure for Wideband C/X/Ku-Band Applications

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Abstract: This research proposes a novel multiband circularly polarised microstrip antenna based on a Swastika-shaped slot and a defected ground structure (DGS). The antenna is implemented on Rogers RT Duroid 5880 substrate measuring $45 \times 45 \times 1.6$ mm³, using a 50Ω microstrip feed line. The antenna design development process starts with a classical circular patch antenna. It is then modified in stages by inserting a Swastik slot, circular perturbation slots, and a DGS to realise multiband behaviour and increase the impedance bandwidth. In addition, a 45-degree rotation of the Swastik slot is added to produce circular polarisation through orthogonally excited modes. The antenna proposed resonates at 6.5 GHz, 10.26 GHz, 14.75 GHz, and 25.75 GHz with reflection coefficients below -14 dB. The realised impedance bandwidths are 1.57 GHz, 2.78 GHz, 4.0 GHz, and 3.5 GHz, respectively. Also, an axial ratio of 0.31 dB with a 3-dB axial ratio (AR) bandwidth of 610 MHz is achieved at 6.25 GHz. The antenna offers stable radiation patterns, with gains ranging from 6.4 dBi to 7.6 dBi across the operating bands. The fabricated prototype was experimentally characterized, and the measured results are presented to validate the simulated performance of the proposed antenna. Due to its small physical dimensions, multiband operation, and generation of circular polarisation, the antenna proposed is a good choice for satellite communications, radar, and advanced wireless communication systems in the C, X, and Ku bands.

Keywords: Microstrip antenna, Multiband antenna, Circular polarization, Swastik slot, Defected ground structure (DGS), Slot-loaded antenna, Wideband antenna

1. Introduction

Its low profile, lightweight, easy fabrication, and adaptability to printed circuits have made microstrip patch antennas widely used in wireless communication systems. This makes them suitable for application in modern communication systems, as well as radar and satellite systems. Nevertheless, conventional microstrip antennas typically lack wideband properties and operate over a limited frequency range. Multifunctional communication systems have become increasingly popular, and there is a need to develop multiband antennas that cover multiple frequency bands within a small footprint. Various slot-loading methods documented in the literature have been shown to broaden bandwidth and develop multiple resonant modes. In this regard, geometric modifications to slots are an efficient way to achieve compact multiband operation. Circular polarisation (CP) is another important parameter in satellite and radar communication systems, as it eliminates polarisation loss and multipath effects.



2. Literature Review

A compact circularly polarised multi-band microstrip patch antenna with a DGS was proposed by Muthukaruppan [1]. The multi-band antenna exhibited multiple resonant bands with improved impedance matching. The DGS technique was shown to be an effective means of achieving circular polarisation. Ambekar et al. [2] have also proposed a dual-band circularly polarised microstrip antenna based on DGS technology. This study showed that perturbing the ground plane can enhance the axial-ratio performance without compromising the antenna's radiation properties. In a subsequent study, Ambekar et al. [3] designed a slot-loaded circular microstrip antenna. The slot design provided the orthogonal resonant modes necessary for circular polarisation.

Gaber et al. [5] studied the characteristic modes of a slot antenna using the DGS concept for a 5G communication system. This research demonstrated the ability of the DGS concept to form multiple resonances and increase impedance bandwidth. Ma and Huang [6] have designed a circular polarised microstrip antenna for aircraft tracking and navigation system applications. In their study, the axial-ratio bandwidth is enhanced via asymmetric structure modification. Khan et al. [7] designed a wideband four-port MIMO circularly polarised antenna using a defected ground structure. The design has shown wideband, high gain, and good polarisation purity suitable for future wireless communication systems. Tran et al. [8] designed a new DGS for a circularly polarised MIMO patch antenna. Improvements in isolation, gain, and circular polarisation properties were observed by optimising the ground-plane structure. Ullah et al. [9] have reported a compact dual-band antenna using pixelated DGS for IoT applications.

Kakkar et al. [10] introduced a triple-band notch microstrip patch antenna based on a fractal-DGS, which successfully increased bandwidth and produced multiple resonant frequencies. Khouser and Choukiker [11] introduced a compact FIN-shaped defected ground structure for antenna arrays. This work successfully minimised cross-polarisation effects while improving radiation properties. Parvez and Haque [12] studied various methods to minimise cross-polarisation effects in wideband slot antennas. In this work, an optimised slot structure was used to minimise cross-polarisation and increase polarisation purity. Daniel [13] presented a multi-band substrate-integrated waveguide antenna incorporating slots, which was optimised using artificial neural networks.

Vadher et al. [14] designed a meandering microstrip leaky-wave antenna that can operate in either linear or circular polarisation mode. The antenna operated at dual frequencies without any effect from open-stopbands. Dhara et al. [15] designed a compact, wideband circularly polarised antenna using a defected ground structure for 5G and Wi-Fi applications, achieving improved bandwidth and gain stability. Balanis [16] laid down the theoretical basis of antennas, including radiation processes, polarisation, and microstrip antenna theory, on which current-day antenna technology is built. Lee and Chen [17] introduced various methods for the design and performance improvement of microstrip and printed antennas, including bandwidth enhancement and multiband antenna design. Garg et al. [18] provided design guidelines for microstrip antennas, including substrate selection, feed designs, and performance enhancement. Pozar [19] introduced principles of microwave engineering and transmission lines, which are widely used in the design and analysis of microstrip antennas.

Pozar and Schaubert [20] developed comprehensive analytical and numerical methodologies for microstrip antenna and array synthesis, laying down the groundwork for contemporary development of patch antennas. James and Hall [21] provided an exhaustive account of the theory of microstrip antenna design and bandwidth-enhancing methods for different communication systems. Wong [22] studied compact and broadband microstrip antenna designs and proposed several approaches for miniaturisation and bandwidth enhancement. Rahmat-Samii and Michielssen [23] discussed genetic algorithm-based approaches to the optimisation of electromagnetic structures, which are currently extensively used to optimise antenna parameters. Anguera et al. [24] reviewed the fractal geometry of antennas which demonstrate the approach to achieve compactness and multiband operation, owing to the self-similarity of these structures. Nasimuddin et al. [25] conducted an exhaustive survey of methods for bandwidth enhancement using the defected ground structure technique.

Despite the significant contributions of research works [1]-[25] have made towards the design of multiband, circular polarisation, and defected-ground antennas, their efforts have mostly concentrated on improving either the

bandwidth, multiband performance, or circular polarisation separately. In addition, some of these reported antennas have complex geometries, multiple layers, or large sizes. Therefore, there is still a need for a small, single-feed antenna that provides multiband performance, improved bandwidth, gain stability, and circular polarisation. In this study, a Swastik slot is cut into a circular patch antenna to provide multiple resonant frequencies. Circular perturbation slots and a defective ground structure are added to enhance the bandwidth performance. Finally, a 45-degree rotated Swastik-slot is used for circular polarisation. This designed antenna operates across multiple bands, with enhanced bandwidth and circular polarisation.

3. Antenna Geometry and Design Evolution

3.1 Antenna Geometry

The geometrical configuration of the proposed antenna is illustrated in Fig. 1, and the optimized design parameters are summarized in Table 1. The designed antenna uses RT-Duroid 5880 material with a relative permittivity ($\epsilon_r = 2.2$) and a dielectric loss tangent of 0.0009, which is 1.6 mm thick. The total size of the substrate remains the same as $45 \times 45 \text{ mm}^2$. The primary radiating structure of the antenna is a circular patch with radius of 13 mm and a 50Ω micro strip line of size $12 \text{ mm} \times 3 \text{ mm}^2$. To make the antenna multiband and circularly polarised, various structural changes are made to the basic circular patch antenna, including a swastika-shaped slot, circular perturbation slots, a DGS, and slot rotation.

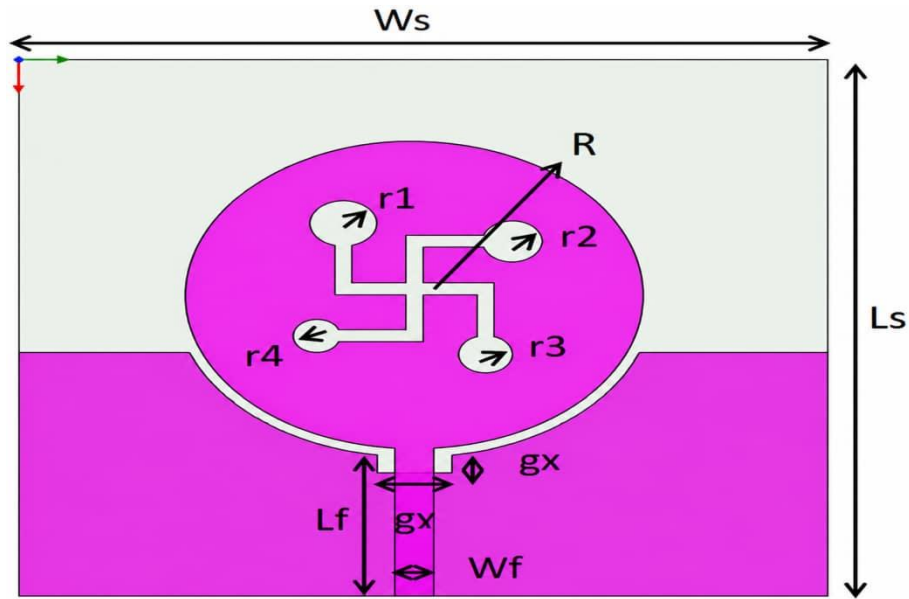


Fig. 1. Proposed multiband circularly polarized antenna geometry.

Table 1 Presented Antenna Dimensions

Parameter	Value (mm)
Substrate Length (L_s)	45
Substrate Width (W_s)	45
Substrate Thickness (h)	1.6
Patch Radius (R)	13
Feed Length (L_f)	12
Feed Width (W_f)	3

Swastik Arm Length (Sx)	6
Swastik Arm Width (Sy)	5
Circle Radius r1	1.9
Circle Radius r2	1.7
Circle Radius r3	1.5
Circle Radius r4	1.3
DGS Gap gx	2
DGS Gap gy	4

3.1.1 Design Equations

3.3 A conventional circular patch antenna was used to develop the proposed antenna. The radius of the circular patch is calculated by applying the cavity model theory as

$$a = \frac{F}{\sqrt{1 + \frac{2h}{\pi \epsilon_r F} [\ln \ln \left(\frac{\pi F}{2h} \right) + 1.7726]}} \text{----- (1)}$$

Where

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\epsilon_r}} \text{----- (2)}$$

where a = patch radius (cm), f_r = resonant frequency (Hz), h = substrate thickness (cm) and ϵ_r = dielectric constant of substrate.

The effective radius of the circular patch is given by

$$a_e = a \sqrt{\frac{2h}{\pi \epsilon_r a} [\ln \ln \left(\frac{\pi F}{2h} \right) + 1.7726]} \text{----- (3)}$$

The resonant frequency of the dominant TM₁₁ mode is expressed as

$$f_r = \frac{1.8412c}{2\pi a_e \sqrt{\epsilon_r}} \text{----- (4)}$$

where c is the velocity of light in free space.

The width of the microstrip feed line corresponding to a characteristic impedance of 50 Ω is determined using

$$Z_0 = \frac{120\pi}{\sqrt{\epsilon_{eff}} \left(\frac{W_f}{h} + 1.393 + 0.667 \ln \ln \left(\frac{W_f}{h} + 1.444 \right) \right)} \text{----- (5)}$$

Where W_f is the feed-line width and ϵ_{eff} is the effective dielectric constant.

Using the above formulas, the original circular patch design was made from RT Duroid 5880 material ($\epsilon_r = 2.2$, h = 1.6mm). Subsequently, the overall antenna design was optimised using the Swastik slot, circular perturbation slots, and DGS.

3.2 Design Development of the Proposed Antenna

This antenna design evolved from a traditional circular patch antenna to a multi-band circular polarisation antenna with a high-impedance bandwidth. The evolution stages are depicted in Fig. 2, and the presentation parameters are outlined in Table 2.

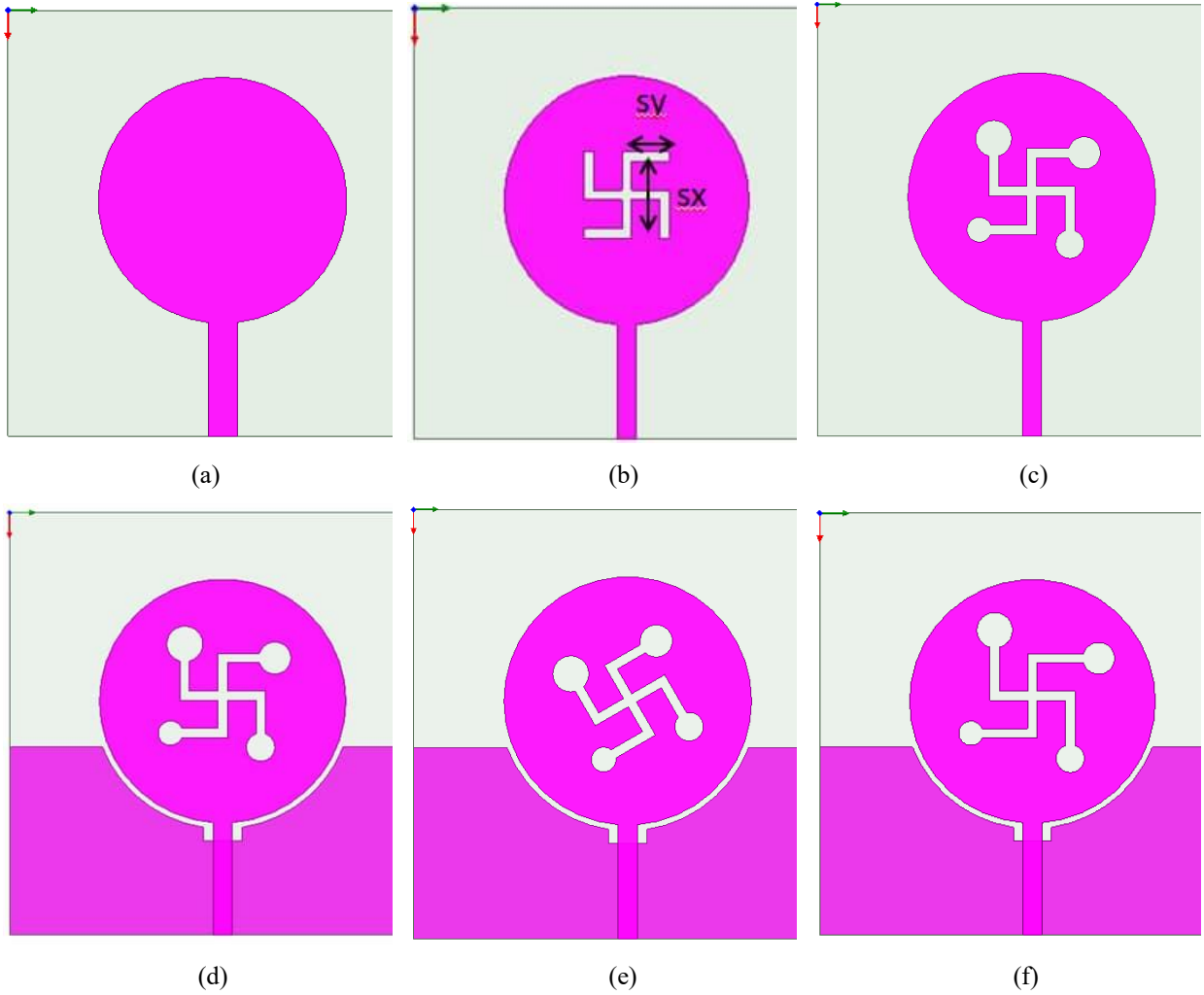


Fig. 2 Stages in the Design Evolution of the Antenna.

Stage 1: Initial Circular Patch Antenna

The first design is a circular microstrip patch of diameter 13 mm, on a substrate of Roger RT Duroid 5880 of $45 \times 45 \times 1.6$ mm³ and fed by a 50Ω microstrip feed line of 12×3 mm² as shown in Fig. 2(a). The antenna has a gain of 6.45 dBi and 12.1 dBi, with an S11 bandwidth of 1.29 GHz to 16.85 GHz, as shown in Fig. 3. However, this antenna can operate only on a few resonant modes and is not a multiband antenna.

Stage 2: Swastik Slot Loaded Circular Patch

To create additional resonances, a Swastik shaped slot is etched on the circular patch as shown in Fig. 2b with dimensions $S_x = 6$ mm and $S_y = 5$ mm. This slot increases the effective length of the current path and adds additional resonances. The antenna thus operates at 8.75 GHz, 18.75 GHz and 21.75 GHz with gains of 9.9 dBi, 7.8 dBi and 9.4 dBi correspondingly. The maximum S11 bandwidth of 2.38 GHz is achieved at 21.75 GHz as shown in Fig. 3 below.

Stage 3: Inclusion of Circular Slots at Swastik Legs

For further improvement in resonant property of the antenna, circular slots of radii $r_1 = 1.9$ mm, $r_2 = 1.7$ mm, $r_3 = 1.5$ mm, and $r_4 = 1.3$ mm were incorporated in the end regions of the Swastik arms of the radiating patch as shown in Fig. 2(c). Circular slots are used as perturbations that disturb the current distribution and effective path length, hence

giving rise to multiple resonant modes. This design allows for a multiband antenna without increasing the antenna dimensions.

With the addition of circular slots, resonant frequency occurs with the gain value of 6.8 dBi, 7.5 dBi, 7.9 dBi, and 9.2 dBi correspondingly. A bandwidth of 1.13 GHz was achieved at 23.25 GHz. In comparison, at 21.25 GHz, the bandwidth obtained is 860 MHz as seen from Fig. 3. Circular slots perform better in resonance generation than the Swastik-slot case.

Stage 4: Introduction of DGS

To further improve the antenna's resonance properties, circular slots of radii $r_1 = 1.9$ mm, $r_2 = 1.7$ mm, $r_3 = 1.5$ mm and $r_4 = 1.3$ mm were embedded at the end of the Swastik arms of the radiating patch as shown in Fig.2(d). These circular slots act as perturbations that modify the surface current pattern and increase the effective electrical length, thus creating additional resonances. In this way, the antenna can achieve multiband characteristics without increasing the physical dimensions of the antenna.

The introduction of the circular slots produces different resonances whose gains are 6.8 dBi, 7.5 dBi, 7.9 dBi and 9.2 dBi. The impedance of bandwidth 1.13 GHz was produced at a frequency of 23.25 GHz. In contrast, an impedance bandwidth of 860 MHz was produced at a frequency of 21.25 GHz as illustrated in Fig. 3. Compared with the Swastik-slot design, the circular slots perform better in terms of resonance generation and multiband characteristics. In this stage, circular polarization occurred at 23.75 GHz with minimum axial ratio of 1.31 dB and a 3-dB axial ratio bandwidth (ARBW) of 430 MHz as shown in Fig.4, thereby proving the orthogonal mode excitation.

Stage 5: Swastik Slot Rotated by 45°

To improve the properties of the circular polarisation, the Swastik Slot is rotated by 45° w.r.t to the feed line, as shown in Fig. 2(e). With this 45° rotation, two currents of same magnitude with a phase difference of almost 90° are produced. This satisfies the requirement of circular polarisation.

For the proposed antenna design, the frequency values were 6.5 GHz, 10.26 GHz, 14.75 GHz, and 25.75 GHz with S11 values of -14.85, -15.36, -29.49, and -27.30 dB, respectively, as shown in Fig.3. Bandwidths increase to 1.57 GHz, 2.78 GHz, 4.00 GHz, and 3.50 GHz. Realised gains have been calculated as 7.6, 6.4, 7.3, and 6.6 dBi, respectively. The most significant feature of this antenna is its axial ratio of 0.31 dB at 6.25 GHz with 3-dB bandwidth of 610 MHz, as seen in Fig.4.

Stage 6: Effect of Increasing Swastik Leg Length

Fourth, the dimensions of the Swastik arms were enlarged to $S_x = 7$ mm and $S_y = 6$ mm to investigate their effect on the antenna's performance as shown in Fig. 2(f). When the slot length is increased, the effective current path is extended, and several resonant modes are overlap in wideband frequencies. Resonance at 6.5 GHz and 25.75 GHz was observed with S11 parameters of -16.83 and -20.74 dB, accordingly. Bandwidths of 11.50 GHz and 4.30 GHz are obtained, as shown in Fig. 3, with gains of 5.2 and 7.5 dBi, accordingly. From the results of this study, it can be seen that the dimensions of the Swastik arms have an important contribution to the resonant frequencies and increasing the bandwidth.

From the evolutionary design process as shown above, the Swastik slot provides multiband operation, circular-perturbation slots introduce further resonant modes, the usage of DGS leads to high bandwidth and gain, and 45° rotation slot allows circular polarisation. Therefore, the output of all these processes will be the design of a multiband circularly polarised antenna for C-, X-, and Ku-bands.

Table 2 Evolution Summary of the Suggested Antenna

Stage	Modification	Resonant Frequency (GHz)	Maximum Gain (dBi)	Remarks
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1	Circular Patch	16.85	12.1	Reference Design
2	Swastik Slot	8.75, 18.75, 21.75	9.9	Multiband Generated
3	Circular Slots	Multiple Bands	9.2	Additional Resonances
4	DGS	6.5, 10.26, 14.75, 25.75	7.1	Bandwidth Improved
5	Rotated Slot	6.5, 10.26, 14.75, 25.75	7.6	Circular Polarization
6	Increased Slot Length	Wideband Response	7.5	Band Merging Effect

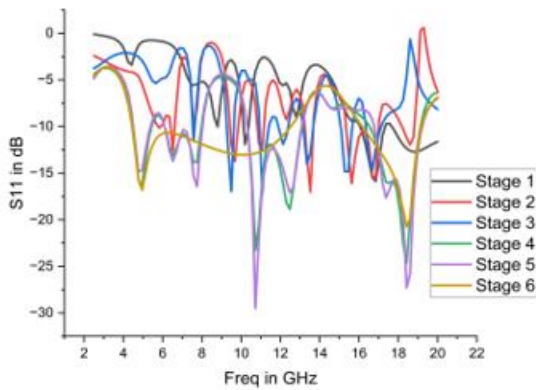


Fig. 3. S11 across the Antenna Evolution Stages

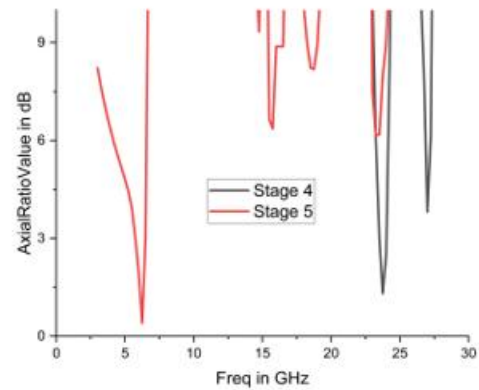


Fig. 4. Axial ratio response of the proposed antenna.

4. Parametric Analysis

4.1 Effect of Circular Slots on Swastik Arms

The impact of circular slots was examined with slot radii of (1.8, 1.6, 1.4, 1.2) mm, (1.9, 1.7, 1.5, 1.3) mm, and (2.0, 1.8, 1.6, 1.4) mm. From Fig. 5, it is obvious that the circular slots significantly affect the antenna's performance. In all the cases, it is observed that for $r_1 = 1.9$ mm, $r_2 = 1.7$ mm, $r_3 = 1.5$ mm, and $r_4 = 1.3$ mm, the deepest resonance is achieved with the best impedance matching.

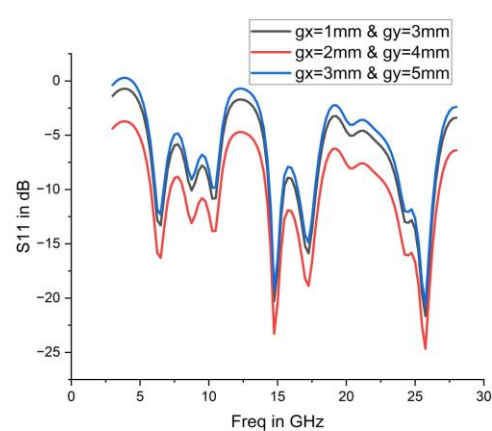
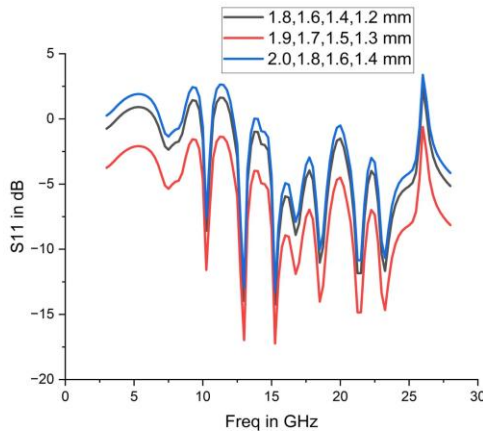


Fig. 5. Effect of circular slots on antenna performance characteristics.

Fig. 6. Effect of DGS on antenna characteristics.

4.2 Effect of DGS

The effect of the DGS was studied by changing the gap parameters (g_x , g_y) to (1 mm, 3 mm), (2 mm, 4 mm), and (3 mm, 5 mm). From Fig. 6, it can be seen that the DGS dimensions significantly affect the resonance frequency and impedance bandwidth. The case where $g_x = 2$ mm and $g_y = 4$ mm shows the best impedance matching and deep resonances in the operating bands. Therefore, this DGS was selected as the optimum DGS structure for the proposed antenna.

4.3 Effect of Swastik Arm Length

The influence of the Swastika arm sizes on the performance was evaluated by changing the size of the arms from $S_x = 6$ mm, $S_y = 5$ mm to $S_x = 7$ mm, $S_y = 6$ mm, as illustrated in Fig. 7. As the size increases, the current path increased, which affects the resonant nature of the antenna. With $S_x = 6$ mm and $S_y = 5$ mm, the antenna exhibits several resonant frequencies with high impedance matching. When the arm sizes are increased to $S_x = 7$ mm and $S_y = 6$ mm, the adjacent resonances combine, resulting in a broadband response.

The new antenna exhibits resonances at 6.5 GHz and 25.75 GHz, with S_{11} of -16.83 dB and -20.74 dB, respectively. The respective bandwidths are 11.50 GHz and 4.30 GHz. Hence, $S_x = 6$ mm and $S_y = 5$ mm were selected for the antenna design.

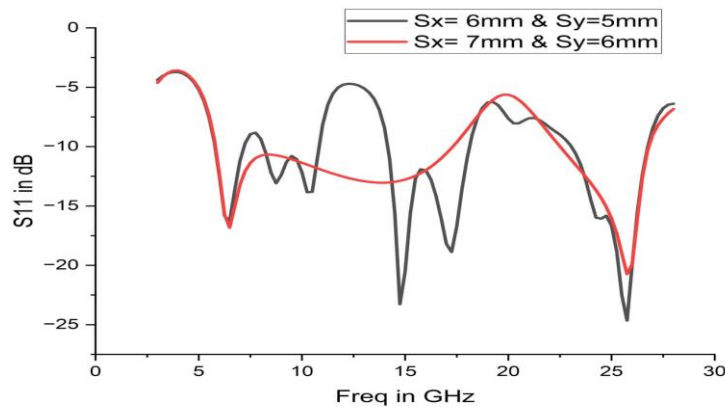


Fig. 7. Effect of Swastik arm-length variation on antenna performance.

The parametric study reveals that circular slots play an important role in multiband performance; DGS provides improvements in impedance bandwidth; rotated 45-degree slots help achieve circular polarisation; and the dimensions of the Swastik arm provide control over resonance and bandwidth. The combination of all the above factors results in the required antenna performance characteristics.

5. Results Analysis and Discussion

This antenna was designed and analysed using Ansys HFSS. The design of this particular antenna involves the use of a circular patch with a rotated 45° Swastik slot, circular perturbation slots, and a DGS. The antenna performance was analysed based on parameters such as return loss, bandwidth, gain, and so forth.

5.1 Reflection Coefficient Characteristics

The simulation of the S_{11} characteristics of the proposed antenna is demonstrated in Fig. 8. The designed antenna has four resonances at 6.5 GHz, 10.26

GHz, 14.75 GHz, and 25.75 GHz having the respective reflection coefficient values of -14.85 dB, -15.36 dB, -29.49 dB, and -27.30 dB. All resonances are in accordance with the impedance matching condition $S_{11} < -10$ dB. The highly prominent resonance occurring at 14.75 GHz is an indication of efficient impedance matching owing to the contributions of the rotated Swastik slot, circular perturbation slots, and the defected ground structure.

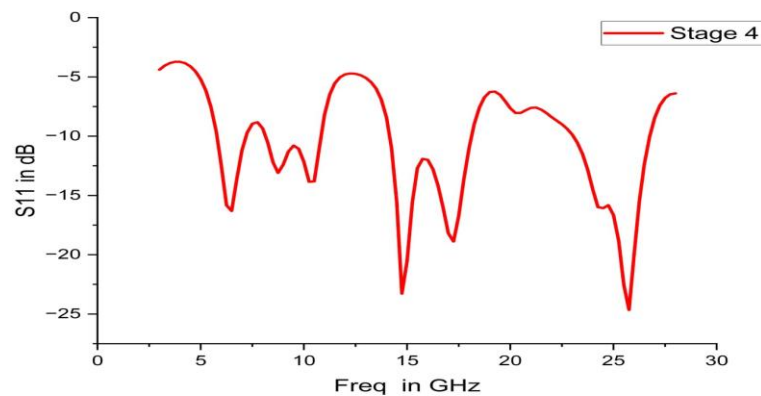


Fig. 8. Simulated reflection coefficient (S₁₁) characteristics of the proposed antenna.

5.2 Gain Characteristics

The gain characteristics of the proposed antenna have been realized as shown in Fig. 9. At the resonance frequencies 6.5 GHz, 10.26 GHz, 14.75 GHz and 25.75 GHz, the peak gains of 7.6 dBi, 6.4 dBi, 7.3 dBi and 6.6 dBi are observed.

In terms of gain characteristics, the antenna shows good stability for the four resonant frequencies with a maximum gain value of 7.6 dBi. Gain improvement can be seen mainly due to the effect of the rotated Swastik-shaped slot and the defective ground structure that contribute to the increase in radiation efficiency of the antenna through providing extra paths of resonant currents and reducing the surface waves on the substrate. Moreover, the optimized slot shape helps to improve the current distribution across the surface of the substrate, which in turn enhances the antenna's impedance and radiation characteristics in spite of the small antenna size.

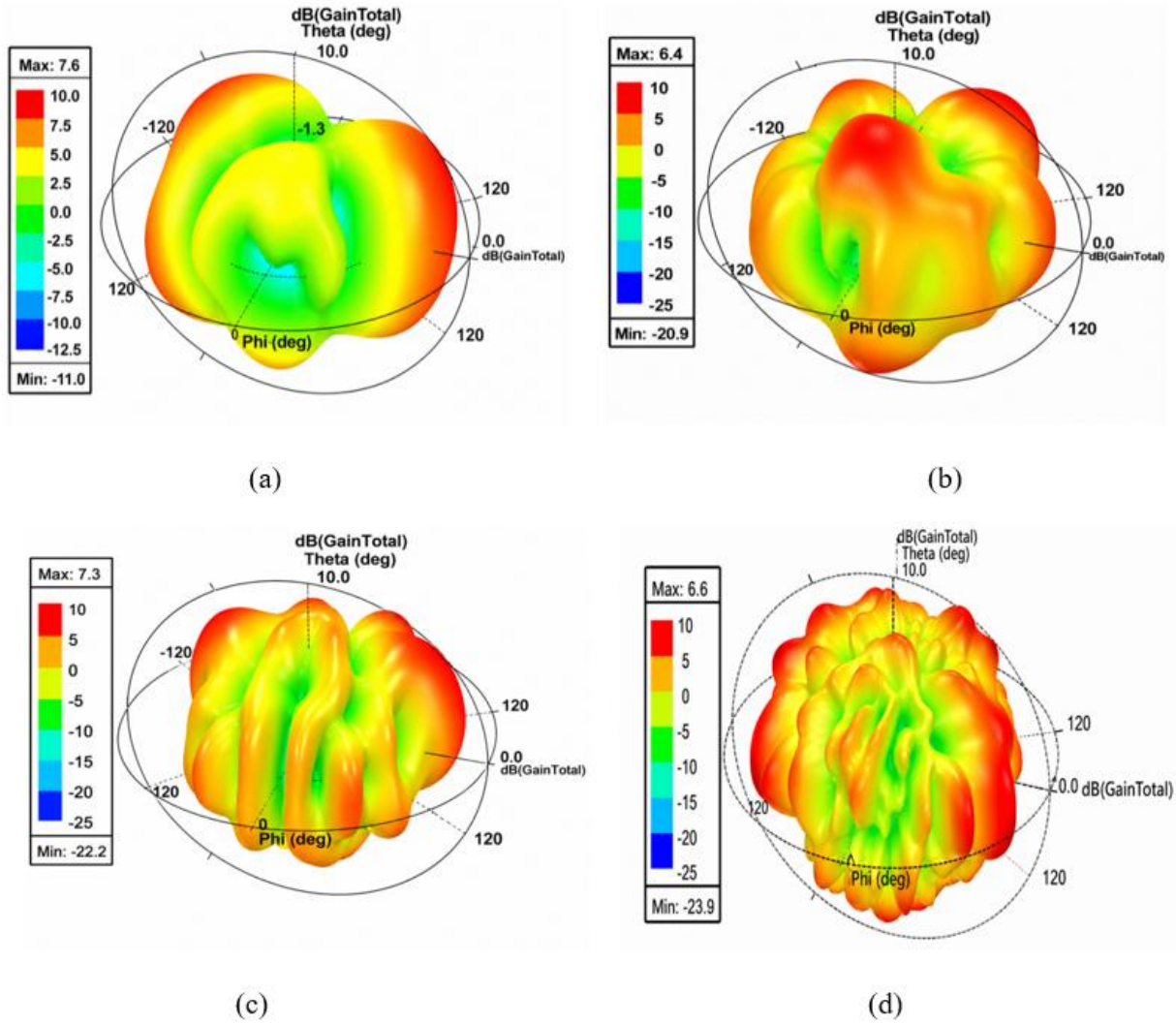


Fig. 9. Realised gain vs. frequency of the proposed antenna at different peaks.

5.3 Axial Ratio Characteristics

The axial ratio behavior for the suggested antenna is depicted in Fig. 10. The minimum axial ratio was 0.31 dB, which was obtained for the main circularly polarized frequency band, thus showing excellent circular polarization characteristics of the designed antenna. The improved axial ratio characteristics can be attributed to the creation of two resonant modes, which have almost the same amplitude and differ by approximately 90° . These modes are created because rotation of the Swastik-slot along with circular perturbation slots.

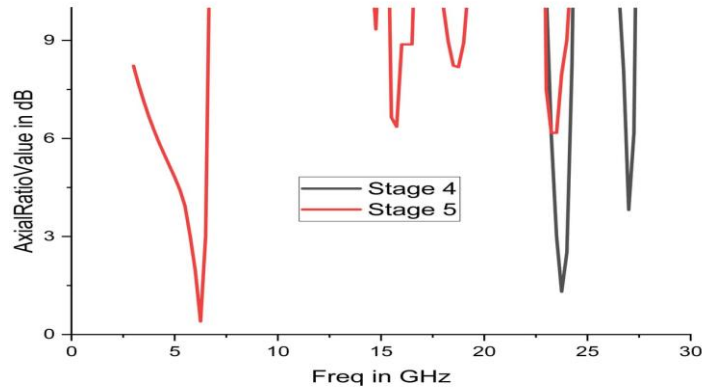


Fig. 10. Axial-ratio characteristics of the presented antenna.

5.4 Surface Current Distribution Analysis

Fig. 11-14 shows the surface current distributions at 6.5 GHz, 10.26 GHz, 14.75 GHz, and 25.75 GHz. The figures show, that there are highly concentrated surface currents in the Swastik slot and the circular perturbation slots. In addition, the surface currents follow different paths at various resonance frequencies, leading to multiple resonance modes.

Surface currents concentrated in the outer region of the Swastik slot give rise to the lowest resonance mode at 6.5 GHz. There are more concentrated currents near the slot junctions and circular perturbation slots at 10.26 GHz and 14.75 GHz, respectively. Finally, high-order surface currents are seen at 25.75 GHz. From these facts, it is clear that the Swastik slot and circular perturbation slots contribute greatly to multiband operation.

$$J_s = n^{\wedge} \times H \text{ ----- (6)}$$

The surface current density depends upon the tangential magnetic field that exists at the surface of the conductor, which can be mathematically represented as in Eq. (6). The use of the rotated Swastik slot, circular perturbation slots, and defected ground structure results in the formation of different paths for the surface currents.

$$E_z(\rho, \phi) = E_0 J_1(k\rho) \cos\phi \text{ ----- (7)}$$

The electric field distribution for the circular microstrip patch is given by Eq. (7). Slot perturbation alters the electric field distribution, leading to the creation of new resonant modes and increased impedance bandwidth.

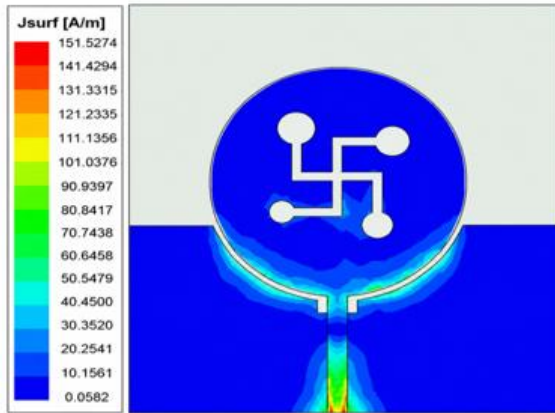


Fig. 11. Current flow distribution at 6.5 GHz.

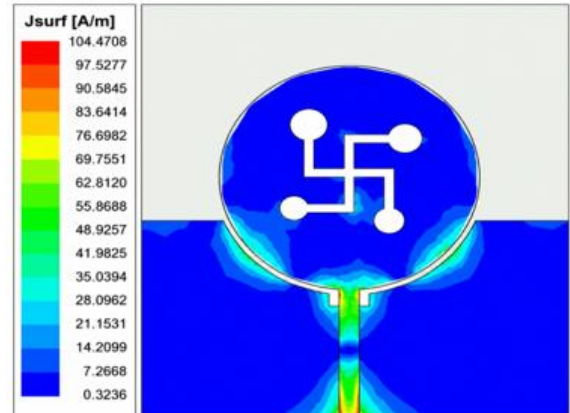


Fig. 12. Current flow distribution at 10.26 GHz.

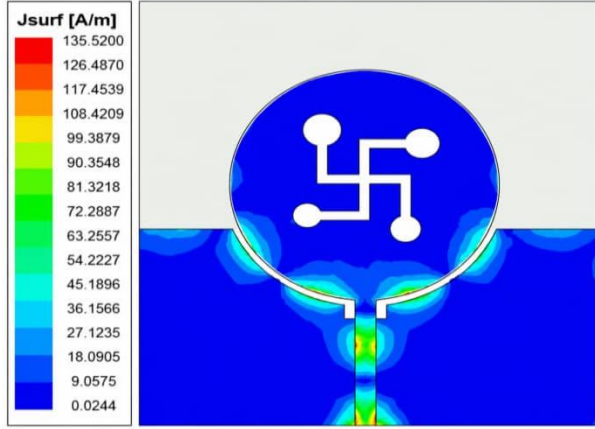


Fig. 13. Current flow distribution at 14.75 GHz.

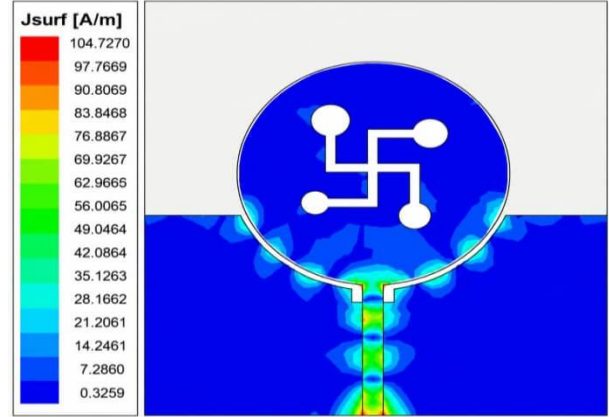


Fig. 14. Current flow distribution at 25.75 GHz.

5.5 Radiation Pattern Analysis

Fig. 15-18 below shows the E and H-plane radiation patterns for the antenna under development. The antenna exhibits good broadside radiation characteristics with good co-polarization performance at the validated operating bands. The measured radiation behavior reveals that the proposed rotated Swastik slot and the defected ground structure (DGS) have improved the impedance matching and radiation efficiency without distorting the far-field characteristics significantly. Slight variations of the beamwidth and the sidelobe levels at higher frequencies are caused by the excitation of higher-order resonant modes typical of multiband microstrip antennas.

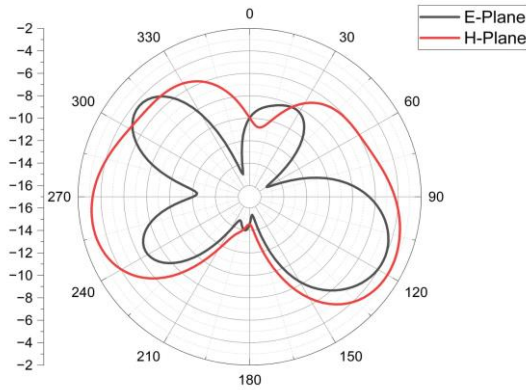


Fig. 15. Radiation pattern at 6.5 GHz.

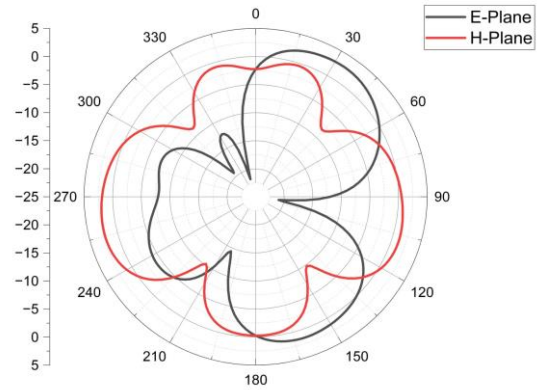


Fig. 16. Radiation pattern at 10.26 GHz.

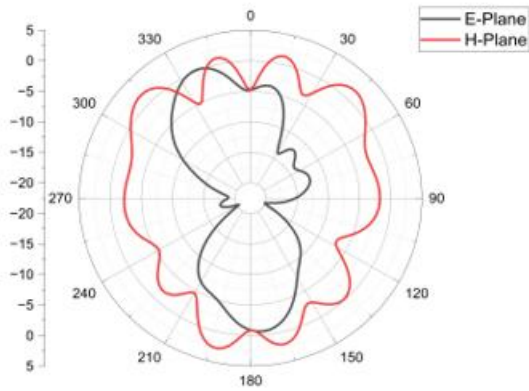


Fig. 17. Radiation pattern at 14.75 GHz.

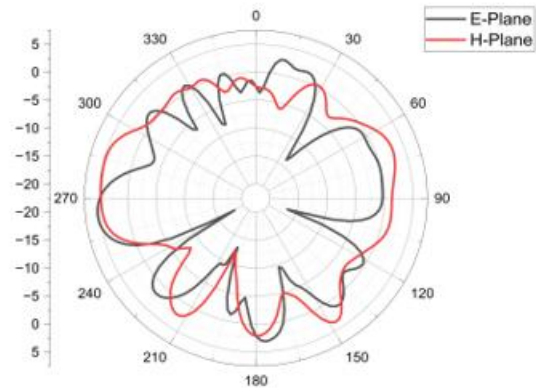


Fig. 18. Radiation pattern at 25.75 GHz.

From the results, it is evident that the presented antenna is suitable for multiband operation, enhanced bandwidth, stable gain, and excellent circular polarisation performance while maintaining a compact geometry.

Table.3 Performance comparison of the suggested antenna with recently reported antennas

Ref.	Antenna Type	Size (mm ²)	Bands	Peak Gain (dBi)	Circular Polarization	Remarks
[2]	DGS Patch Antenna	40 × 40	2	6.1	No	Compact structure
[3]	Swastik Slot Antenna	45 × 45	3	6.5	No	Multiband operation
[5]	DGS-Based CP Antenna	50 × 50	2	6.2	Yes	Improved AR
[12]	DGS Multiband Patch	55 × 55	3	6.5	No	Enhanced bandwidth
[18]	Multiband DGS Antenna	52 × 52	3	6.3	No	Compact design
[19]	Circular Patch with Slots	45 × 45	2	6.8	Yes	Moderate bandwidth
[20]	CP Microstrip Antenna	50 × 50	2	6.5	Yes	Stable radiation
[21]	Multilayer Patch	65 × 65	3	7.5	Yes	Larger size
[22]	DGS Circular Patch	55 × 55	2	6.7	No	Enhanced bandwidth
[23]	Wideband CP Antenna	60 × 60	2	7.1	Yes	Wide AR bandwidth
[24]	Slot-loaded DGS Antenna	50 × 50	3	6.8	No	Multiband response
Proposed	Swastik Slot + Circular Slots + DGS	45 × 45	4	7.6	Yes	Compact multiband CP antenna

Comparison of the suggested antenna to other multiband and circularly polarized antennas, which have been published in recent literature, is carried out in Table 3 according to antenna size, number of operational bands, peak gain, and polarization performance. It can be seen from the table that the suggested antenna provides a good compromise between antenna size, four bands of operation, circular polarization, and gain. Although there are antennas, that offer more gain and/or bandwidth, their size is much bigger, and they consist of many layers and have fewer bands of operation.

5.6 Fabrication and Experimental Validation

To verify the simulated results, a prototype antenna was manufactured and characterised using a Keysight FieldFox microwave analyser. Fig.19 shows the manufactured prototype and the measurement setup. Figures 19(a) and 19(b) show the front and rear views of the manufactured prototype antenna, respectively, whereas the measurement setup for S-parameter characterisation is shown in Fig. 19(c).

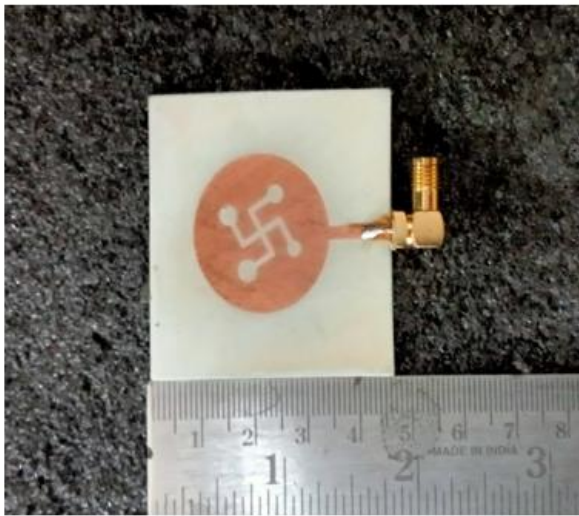


Fig. 19(a). Front view of the fabricated antenna.



Fig. 19(b). Back view of the fabricated antenna.



Fig. 19(c). Experimental setup using the Keysight FieldFox microwave analyser.

5.6.1 Measured and Simulated Reflection Coefficient

To prove the validity of the simulated performance, the designed antenna was fabricated on a Rogers RT/Duroid 5880 material and tested using a Keysight FieldFox VNA. Fig. 20 shows the comparison of the simulated and measured reflection coefficient (S_{11}) performances. A good match has been observed between the simulated and measured results in the range where measurements are feasible (3-18 GHz), which proves the multiband nature of the designed antenna. Some difference between the resonant frequencies and return loss values may have been due to the tolerance in fabrication, SMA connector soldering, change in dielectric constant of the substrate, and measurement errors. It must be kept in mind that the VNA available for measurements works up to 18 GHz only; therefore, simulation of the 25.75 GHz resonance could not be verified experimentally.

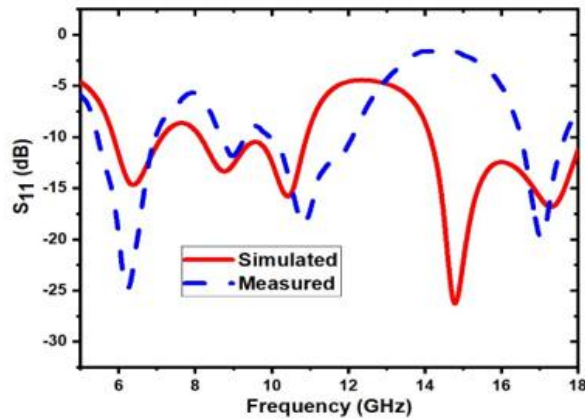


Fig. 20. Validation of the proposed antenna using simulated and measured S_{11}

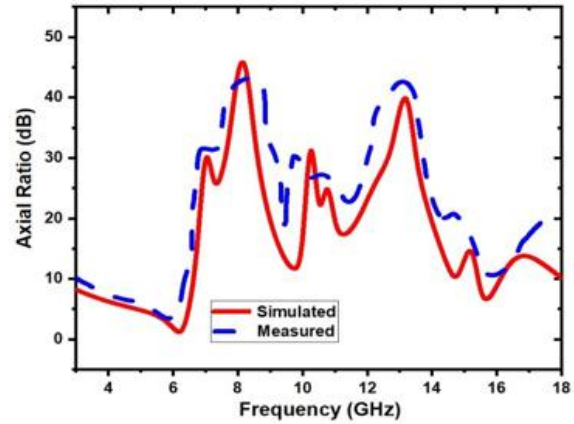


Fig. 21. Validation of circular polarization through simulated and measured axial-ratio results.

5.6.2 Measured and Simulated Axial Ratio

Fig. 21 shows the comparison of the simulated and measured axial-ratio properties of the proposed antenna. As can be seen from the results obtained from the measurements, there is a good match with the simulations for the range of frequencies covered by the test equipment, hence verifying the circular polarization properties of the proposed antenna. There are some minor differences between the simulated and measured axial ratio since some factors such as fabrication errors, property variation, and connectors affect the measurements. Given that the test facility only goes up to 18 GHz, it was not possible to verify the circular polarization behavior at higher frequencies through measurements.

5.6.3 Measured and Simulated Radiation Pattern

The radiation patterns simulated and measured for the E-plane and H-plane at the selected frequencies of operation are shown in Fig. 22 below. The experimental radiation patterns closely match the simulation results, which show that the proposed antenna achieves steady broadside radiation in the range of frequency experimentally verified. Small differences in sidelobe levels and beam shapes may be caused by manufacturing tolerances, misalignment during measurement, SMA connectors and reflections from environment during measurement. From the experimental results, it is clear that the simulations are well supported, hence the proposed antenna is suitable for multiband wireless/radar communications applications in the specified frequency range.

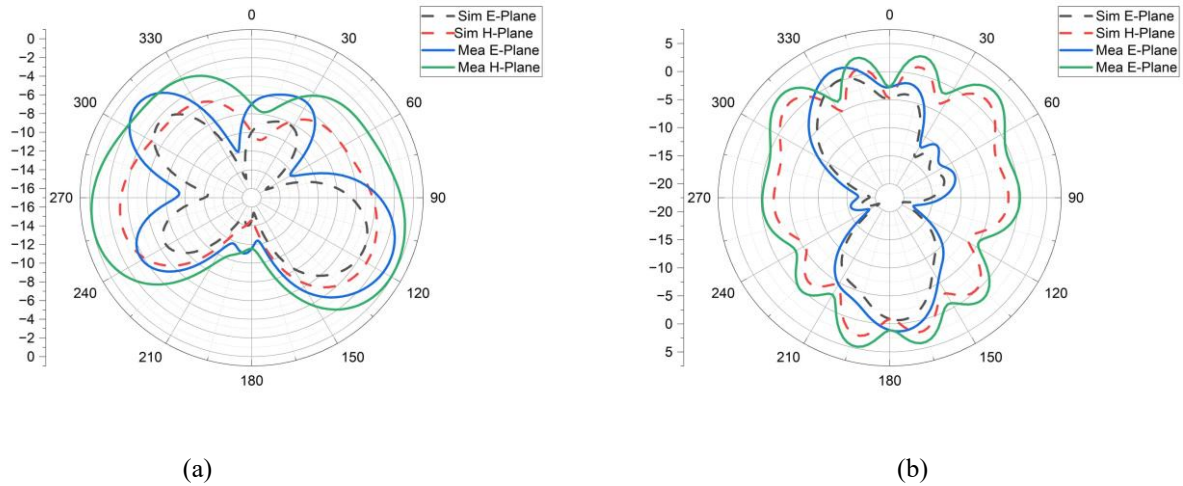


Fig. 22. Simulated and measured radiation patterns (a) at 6.5 GHz (b) at 25.75 GHz

5.7 Limitations of the Present Study

In spite of promising results of multiband operation, good circular polarization and stable radiation performance achieved with the proposed antenna, we should mention the following shortcomings: Firstly, due to frequency constraints of the employed Keysight FieldFox Vector Network Analyzer, the experimental verification only carried out until 18 GHz and the simulated resonance frequency 25.75 GHz was not measured. Secondly, we only characterized a single prototype of the manufactured antenna in laboratory environments and the effect of manufacturing variability and the environmental condition was not addressed. Our future works include full-band experimental verification with high-frequency measurement devices, study on manufacturing variability, and testing the antenna in real environments.

6. Conclusion

A compact Swastik-slot based circularly polarized microstrip antenna featuring circular perturbation slots and defected ground structure (DGS) is designed and analyzed for its applications in multi-band C-, X-, and Ku-bands. This antenna shows four resonant frequencies at 6.5 GHz, 10.26 GHz, 14.75 GHz, and 25.75 GHz and provides reasonable impedance match ($S_{11} < -10$ dB), constant realized gain, and good circular polarization behavior. In the proposed configuration, the maximum achieved realized gain and minimum axial ratio are 7.6 dBi and 0.31 dB, respectively. The proposed antenna could be experimentally characterized only up to 18 GHz due to the frequency limitation of the available experimental measurement setup, and therefore the resonance at 25.75 GHz was validated through simulation only.

All things considered, the proposed antenna has shown great promise in terms of its operation for use in compact multiband wireless and radar communication systems in C, X, and Ku-band frequencies. However, more tests are required to be conducted for full confirmation of the operational ability of the antenna in all the operational frequencies and in practice as well.

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Authors state no funding involved.

DATA AVAILABILITY

The data used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

J Nageswara Rao : Conceptualization, Literature Review, Model Development, Experiment Implementation, Manuscript Drafting;

R Ramana Reddy : Supervision, conceptual guidance, methodology review, validation, interpretation of results, critical review and editing of the manuscript

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