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A Compact Triple-Band Microstrip Antenna Using Inclined Rectangular Slots and Semi-Octagonal Defected Ground Structure for Wireless Applications

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ABSTRACT

This work discusses the design and performance analysis of a small, multi-band slot-loaded octagonal microstrip patch antenna with a defected ground structure (DGS). The proposed antenna has been implemented using an FR4 substrate having a dielectric constant of 4.4, a thickness of 1.6 mm, and dimensions of 30 x 35 x 1.6 mm^3. The evolution of this antenna begins with a basic circular patch radiating element with a radius of 7.2 mm, a resonant frequency of 9.69 GHz, a return loss of -15.44 dB, an impedance bandwidth of 1.19 GHz, and a gain of 4.5 dBi. To improve the antenna's operating parameters, the circular radiator has been modified to an octagonal shape and further incorporated with circular, rectangular, and inclined rectangular slots. This will introduce new resonant frequencies and increase the antenna's radiation efficiency. Extensive parametric studies have been conducted to examine the effects of slot shapes, slot orientations, and ground-plane changes. The designed antenna operates as a dual-band system with resonance at 6.5 GHz and 10.67 GHz. The antenna's return loss is -24.28 dB, and the impedance bandwidth is 2.03 GHz at 6.5 GHz; at 10.67 GHz, the return loss and bandwidth are -13.03 dB and 770 MHz, respectively. The corresponding gains for both frequencies are 4.0 dBi and 4.2 dBi, respectively. The design offers substantial bandwidth improvements, compactness, and robust radiation properties, making it ideal for radar, satellite communications, microwave sensing, and related applications.

INTRODUCTION

Microstrip patch antennas have emerged as one of the most extensively utilised radiators for modern wireless communication systems owing to their compact size, light weight, relatively inexpensive fabrication process, and ability to be fabricated on microwave integrated circuit boards. These antennas have found many uses in radar technology, satellite communication, wireless local area networks (WLAN), remote sensing, and military communication systems. Among the different frequency bands, the X band (8-12 GHz) plays a very important role owing to its extensive use in radar tracking, satellite communication, navigation, and imaging systems. Although these types of antennas have many useful properties, their performance is usually hindered by a narrow impedance bandwidth, poor gain, and limited frequency band operations.

To address the above-discussed disadvantages, several efforts have been made in the design of multiband antennas. A multiband antenna operates across multiple bands using a single radiating element and thus offers low system complexity, compactness, and low fabrication cost. Multiband antennas are therefore highly required in today's wireless communication systems that operate simultaneously across multiple frequency bands. Many methods have been used to design and modify antennas to achieve multiple frequency bands within a reduced antenna structure.

Among the methods used to broaden antenna bands, slot loading is among the most promising due to its ability to cover multiple operating bands. Slotting increases bandwidth by altering the surface current distribution and

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extending the effective length of the current path, thereby enabling multiple resonance modes. In addition, many slot geometries, including circular, rectangular, U-shaped, C-shaped, and fractal slots, have been shown to improve the antenna's bandwidth and radiation pattern.

Another promising technique for performance enhancement is the implementation of Defected Ground Structures (DGS). A DGS is created by intentionally introducing defects or slots in the ground plane, altering the current distribution and electromagnetic characteristics of the antenna. The incorporation of DGS can improve impedance bandwidth, reduce return loss, enhance gain, suppress surface waves, and provide better radiation efficiency. Furthermore, combining slot-loading techniques with DGS has been shown to provide substantial improvements in bandwidth and multiband characteristics while maintaining compact antenna dimensions.

LITERATURE REVIEW

In their paper, Therase and Thangappan introduced a microstrip antenna integrated with CRR DGS, operating in the X band. The antenna operated in dual bands at 9.7 GHz and 11.4 GHz, demonstrating improved gain, directivity, and radiation efficiency. The authors highlighted the significance of DGS in improving antenna performance through their experiments. The main contribution of the work is the improvement in dual-band performance, achieved without studying the mechanism underlying multiresonant slots [1]. Nayna et al. designed a diamond-shaped slot, along with a ring structure, on a rectangular patch antenna and a defected ground plane to achieve high-bandwidth performance. They obtained a bandwidth of about 512 MHz around the centre frequency of 10 GHz, with satisfactory impedance-matching characteristics. The design showed an increase in bandwidth, but there was no discussion of the design evolution [2].

In addition, Nayna, Ahmed, and Haque made further advances in this regard. She designed a circular patch antenna with a diamond-shaped slot and a DGS structure for ultra-wideband applications. This type of antenna showed a bandwidth of up to 506 MHz in the X band and exhibited enhanced return loss. Gain improvement and multiband features were still poor [3]. Guha and Biswas have studied multiband microstrip antennas with defected ground structures to reduce mutual coupling and improve radiation. They demonstrated that the DGS could be used effectively to create multiple resonances and enhance bandwidth. At the same time, the structures developed were more complicated than usual patch designs [4]. An inverted F-shaped defected ground structure for broadband microstrip antenna design has been discussed by Ali et al. The modified ground plane resulted in enhanced impedance bandwidth and return loss performances[5-6].

Kandwal et al. designed a Z-shaped defected ground structure to enhance the bandwidth of microstrip antennas. With the addition of DGS, the distribution around the radiating patch changed, leading to an enhanced impedance bandwidth and improved matching. Unfortunately, this design did not use slot-loading technology in the radiating patch [7]. Ghosal et al. studied the effects of slot loading in microstrip antennas by applying the characteristic mode analysis technique. They showed that the orientation of slots played an important role in influencing the current distribution, resonant frequency, bandwidth, and radiation pattern. This was an insightful study concerning the importance of proper slot orientation in the creation of other resonant modes [8]. Karahan et al. designed a miniaturised microstrip patch antenna operating at 10 GHz for X-band applications. The antenna had desirable radiation characteristics and gain for its application in wireless communication systems, but lacked slot loading or DGS techniques to enhance its bandwidth [9].

A compact dual-band circularly polarised microstrip antenna with concentric patches and slot perturbation techniques was designed by Ghosal & Shubair. The designed antenna offered a dual-band CP performance, while keeping the overall size compact. Although successful in providing diversity in polarisation, the proposed antenna design paid little attention to enhancing the system's bandwidth [10]. A fractal microstrip patch antenna with a partial ground-plane configuration and a genetic algorithm optimisation process was introduced by Rasheda et al. The fractal antenna showed improved gain and frequency-band performance through geometric optimisation. Nevertheless, due to the complex optimisation process, designing a fractal antenna requires more effort than designing a slot-loaded antenna [11-12].

According to the literature review, many antennas use either slot loading or the defective ground structure technique, but these concepts have not been considered together. Very few works discuss circular-to-octagonal shape radiators with inclined slots and DGS. Thus, the present work aims to introduce a new compact slot-loaded octagonal microstrip antenna with a semi-octagonal DGS to achieve optimal bandwidth and gain characteristics.

Antenna Geometry and Design Methodology

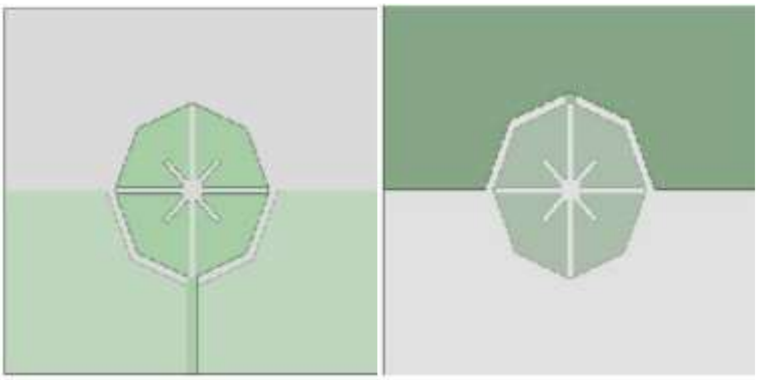
The geometry of the proposed antenna is shown in Fig. 1 below. The proposed antenna structure is designed on a FR4 substrate with a permittivity (εr) of 4.4, a loss tangent of 0.02, and a thickness of 1.6

mm. The overall size of the substrate is 30 mm × 35 mm × 1.6 mm³. A 50 Ω microstrip feed line is used to excite the radiating element for proper impedance matching.

The process of designing an antenna starts by designing a simple circular microstrip patch with a radius of 7.2 mm. The radiator's circular shape will be modified to an octagonal shape to improve current distribution in the resonant mode. To create more resonant modes and achieve efficient impedance matching, a circular slot 1 mm in radius is cut in the centre of the radiator. In addition to that, two rectangular-shaped slots of size 6.2 mm × 0.5 mm are created on the radiating element. The number of these slots will increase incrementally to assess their effects on resonant frequencies and gains.

As another means of enhancing antenna performance, rectangular slot inclusions measuring 3.5 mm x 0.5 mm are introduced at a 45° angle to the patch antenna axis. The inclusion of such slots increases the current path length and enables the excitation of additional resonances, thereby improving multi-band performance. A parametric study is conducted on different arrangements of these slots to determine the optimal configuration for the antenna.

As the final step in the antenna design, a Defected Ground Structure (DGS) is added to the back of the substrate. A semi-ground structure having semi-octagonal slots is used to perturb the current distribution in the ground and achieve a wider impedance bandwidth. Moreover, the use of DGS reduces the return loss and enhances the radiation pattern. With the optimised antenna configuration, two bands are obtained around 6.5 GHz and 10.67 GHz.



(a) (b)

Fig.1: Proposed antenna geometry (a) Front view, (b) Back view (DGS)

The design development process for the designed antenna is shown in Fig. 2, where the antenna starts with a basic circular patch antenna and evolves into a slot-loaded octagonal antenna incorporating a semi-octagonal DGS. The geometric dimensions optimised for this antenna design are given in Table 1.

Table 1. Dimensions of the proposed antenna

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Parameter	Description	Value (mm)
Ls	Substrate Length	35
Ws	Substrate Width	30
h	Substrate Thickness	1.6
R	Circular Patch Radius	7.2
R1	Circular Slot Radius	1
Lr	Rectangular Slot Length	6.2
Wr	Rectangular Slot Width	0.5
Li	Inclined Slot Length	3.5
Wi	Inclined Slot Width	0.5
θ	Inclined Slot Angle	45°
Wf	Feed Width	1
Lf	Feed Length	8

Antenna Evolution and Parametric Analysis

To increase bandwidth and multiband capability, the designed antenna is obtained through a series of 12 design iterations, in which each iteration includes a modification to the radiating patch or ground plane, and the effect on antenna properties is examined using electromagnetic simulation. Through these design iterations, one can easily comprehend the significance of different parameters for achieving impedance match, bandwidth, and gain improvements.

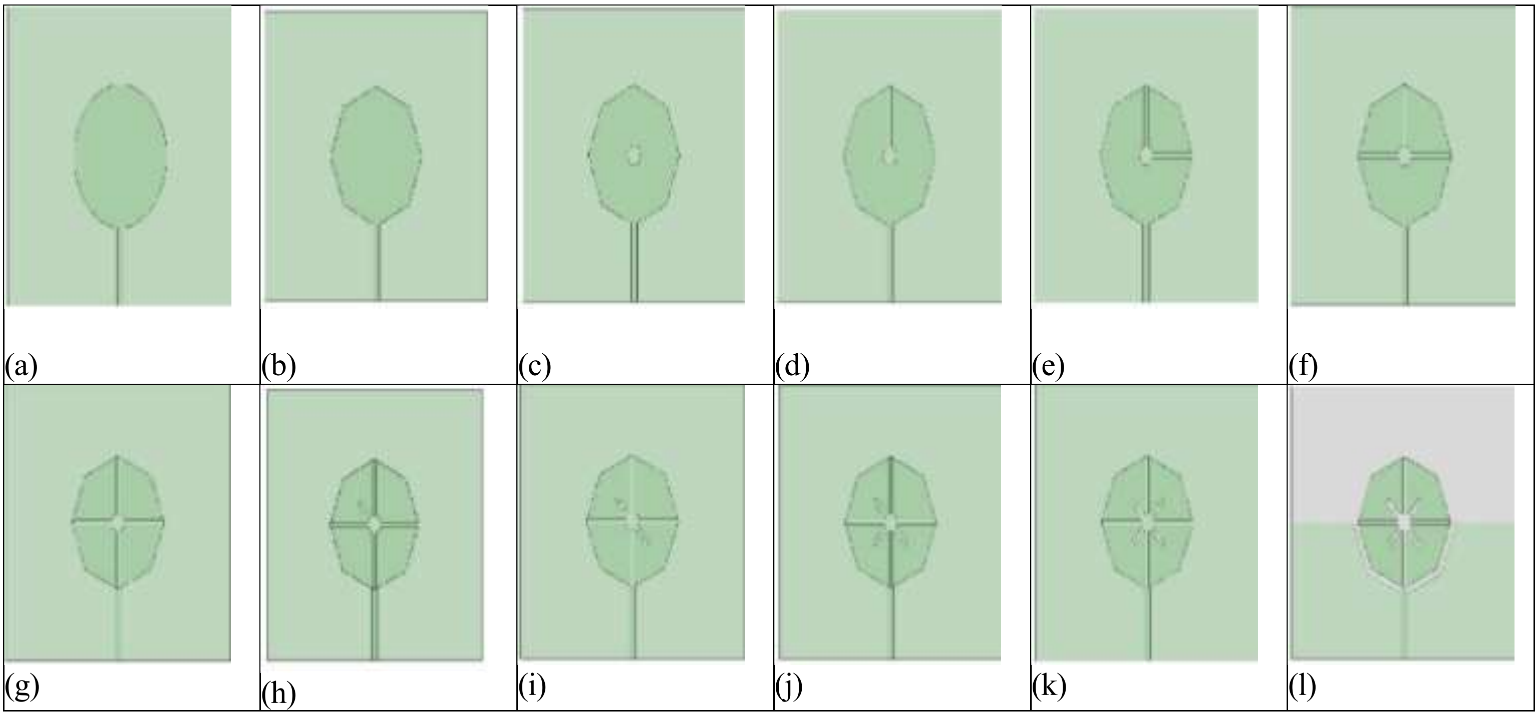

Figure 2: Antenna evolution stages

Stage 1: Circular Patch Antenna

The first antenna design comprises a circular microstrip patch with a diameter of 7.2mm, mounted on an FR4 substrate, as illustrated in Fig. 2(a). The resonance frequency of the antenna is 9.69 GHz, with a return loss of −15.44dB and an impedance bandwidth of 1.19 GHz, as illustrated in Fig. 3. The gain of this antenna design is 4.5 dBi. While good matching performance is exhibited, the antenna operates at a single band.

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Stage 2: Octagonal Patch Antenna

In stage two, the patch is modified to have an octagonal radiator shape, as illustrated in Fig. 2 (b). In this case, there is a change in the surface current distribution, resulting in good impedance matching. At a resonance frequency of 9.90 GHz, there is a return loss of −23.06 dB with a bandwidth of 560 MHz, as illustrated in Fig.3.

Stage 3: Circular Slot Incorporation

A circular slot with a radius of 1 mm is cut at the centre of the octagonal patch, as illustrated in Fig.

2(c). The slot helps to change the current flow and improve resonance properties. The designed antenna operates at 9.90 GHz with a return loss of -23.68 dB, a bandwidth of 550 MHz, as indicated in Fig. 3, and a gain of 4.0 dBi.

Stage 4: Single Rectangular Slot

A slot measuring 6.2 mm × 0.5 mm is created on the radiating patch as illustrated in Fig.2 (d). This slot disrupts the current distribution, thereby improving impedance matching. It can achieve a return loss of-24.11 dB at 9.90 GHz, with an operating bandwidth of 550 MHz, as illustrated in Fig. 3, and a gain of4.3 dBi.

Stage 5: Two Rectangular Slots

Now there are two rectangular slots in addition to those from the previous designs. As seen in Fig. 2 (e), an additional resonant frequency occurs at 6.47 GHz. Hence, the antenna is designed for dual-band operation at 6.47 GHz and 9.90 GHz, as shown in Fig. 3. The antenna gains are 4.3 dBi and 5.7 dBi at6.47 GHz and 9.90 GHz, respectively.

Stage 6: Three Rectangular Slots

However, the addition of a third rectangle slot depicted in Figure 2 (f) results in triple band behaviour due to additional alteration of current flow. The resonances occur at 6.89 GHz, 10.04 GHz, and 11.23 GHz, respectively, with gains of 5.2 dBi, 5.1 dBi, and 4.7 dBi, as demonstrated in Figure 3.

Stage 7: Four Rectangular Slots

With the addition of four rectangular slots (Fig. 2 g), better matching has been achieved across several frequencies. Resonance occurs at 6.96 GHz, 9.90 GHz, and 11.23 GHz (Fig. 3), with gains of 5.4 dBi,4.4 dBi, and 4.5 dBi, respectively. Return loss has been improved to –29.06 dB at the second resonance.

Stage 8: Single Inclined Slot Inclusion

A small, rectangular-shaped slit of size 3.5 mm × 0.5 mm, inclined at 45°, has been incorporated, as illustrated in Fig. 2(h). As a result of incorporating the inclined slit, the total surface current length path becomes greater, thereby producing three resonant frequencies 6.40GHz, 9.76GHz, and 11.23GHz, as illustrated in Fig.3. There is a considerable increase in bandwidth up to 900MHz at the third resonance.

Stage 9: Two Inclined Slot Inclusions

Figure 2(i): The inclusion of a second inclined slot enhances the impedance match and increases stability for the multiband operation. The antenna operates at 6.75 GHz, 9.83 GHz, and 11.23 GHz, achieving a minimum return loss of -32.06 dB at the second frequency, as shown in Figure 3.

Stage 10: Three Inclined Slot Inclusions

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Three slot inclusions with inclination have been used in this antenna design as depicted in Fig. 2 (j). The gains are found to be 5.1 dBi, 5.9 dBi, and 5.0 dBi at 6.75 GHz, 9.83 GHz, and 11.23 GHz, respectively, as depicted in Fig. 3. This is the peak gain achieved throughout the design process.

Stage 11: Four Inclined Slot Inclusions

The inclination of slots according to Fig. 2(k) also maintains the multi-band property while preserving impedance matching. The antenna operates at 6.89 GHz, 9.83 GHz, and 11.30 GHz, as shown in Fig. 3. The gains in each band exceed 4 dBi.

Stage 12: Defected Ground Structure (DGS)

At this last stage, a semi-octagonal defective ground structure has been introduced on the back side of the substrate, as depicted in Fig. 2(l). The use of DGS helps improve impedance bandwidth and alter resonant behaviour. The optimised antenna operates at dual frequencies of 6.5 GHz and 10.67 GHz, with return losses of −24.28 dB and −13.03 dB, respectively, as illustrated in Fig. 3. Their respective bandwidths are 2.03 GHz and 770 MHz, and gains of 4.0 dBi and 4.2 dBi are achieved.

DISCUSSION

From the results presented above, it is evident that the use of octagonal patches, slot loading, slot inclinations, and DGS is critical in enhancing the performance of the antenna under consideration. Slot loading creates multiple resonant frequencies, enabling the antenna to operate over different frequency bands. On the other hand, the DGS has been observed to improve the impedance bandwidth, as seen from Table 2. Hence, the design achieves excellent bandwidth.

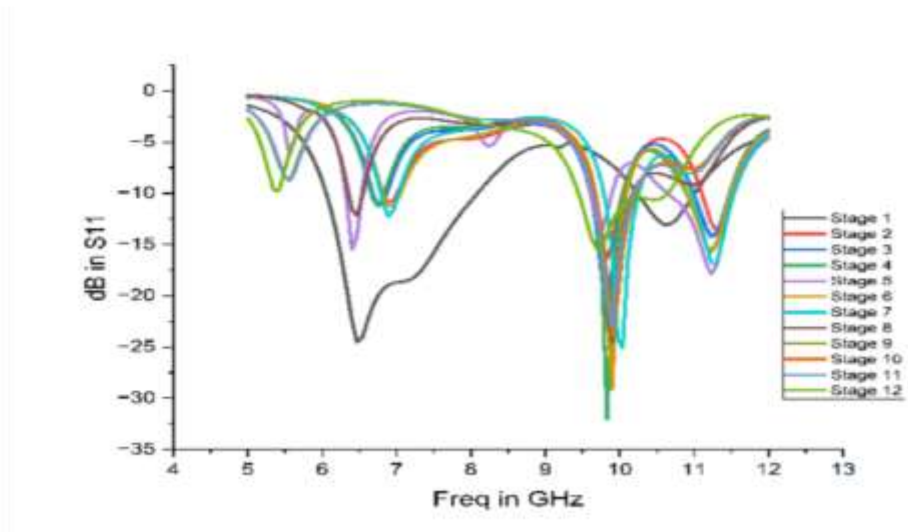

Fig. 3: S11 comparison of all stages

Table 2: Evolution summary (Frequency, RL, BW, Gain)

Phase	Antenna Evolution	Resonant Frequencies (GHz)	urn Loss (dB)	andwidth (MHz)	ɛak Gain (dBi)
1	Circular Patch	9.69	-15.44	1190	4.5
2	Octagon Patch	9.90	-23.06	560	4.1
3	Circular Slot Introduced	9.90	-23.68	550	4.0
4	Single Rectangular Slot	9.90	-24.11	550	4.3

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5	Two Rectangular Slots	6.47 / 9.90	-12.21 / -24.51	190 / 530	4.3 / 5.7
6	Three Rectangular	6.89 / 10.04 / 11.23	-12.26 / -25.11	140 / 460 / 570	5.2 / 5.1 /
	Slots		/ -16.76		4.7
7	Four Rectangular	6.96 / 9.90 / 11.23	-11.25 / -29.06	230 / 400 / 590	5.4 / 4.4 /
	Slots		/ -15.74		4.5
8	One Small Inclined	6.40 / 9.76 / 11.23	-15.53 / -13.76	210 / 280 / 900	2.7 / 4.5 /
	Slot		/ -17.86		4.4
9	Two Small Inclined	6.75 / 9.83 / 11.23	-11.27 / -32.06	180 / 410 / 600	4.8 / 4.3 /
	Slots		/ -15.67		4.3
10	Three Small	6.75 / 9.83 / 11.23	-11.28 / -22.53	190 / 440 / 490	5.1 / 5.9 /
	Inclined Slots		/ -14.21		5.0
11	Four Small Inclined	6.89 / 9.83 / 11.30	-10.91 / -16.39	190 / 410 / 410	5.3 / 4.3 /
	Slots		/ -13.65		4.7
12	DGS (Semi-Octagonal Slot)	6.50 / 10.67	-24.28 / -13.03	2030 / 770	4.0 / 4.2

Parametric Analysis of DGS Depth

The impact of DGS on antenna performance was investigated by varying the depth of the semioctagonal slot on the ground plane while keeping all other antenna parameters constant. In this case, the depth of the DGS determines the current distribution as well as the electromagnetic coupling between the radiating element and the ground plane. An increase in the DGS depth alters the effective capacitance and inductance of the antenna structure, leading to slight changes in the resonant frequency and bandwidth. At first, increasing the DGS depth led to better impedance matching and a wider bandwidth, due to improved current perturbation. However, excessive DGS depth led to a decline in antenna performance, with a shift in resonance and poor impedance matching. Hence, the optimum DGS depth that provided the maximum bandwidth enhancement while maintaining good gain and radiation pattern was determined. Bandwidth enhancement from this process was found to be 2.03 GHz in the lower band and 770 MHz in the upper band, as illustrated in Fig. 4.

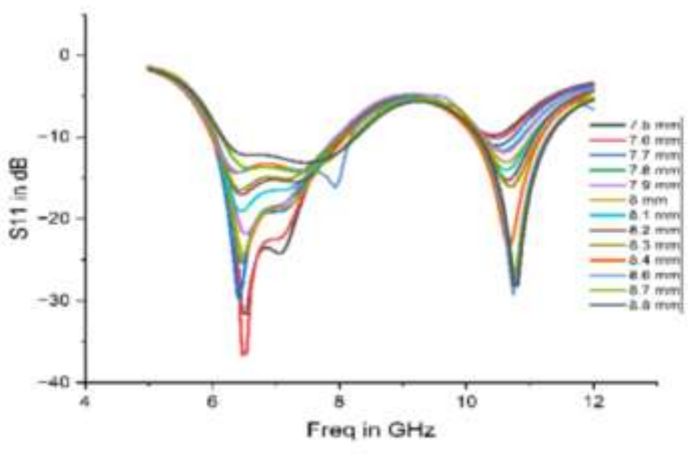

Fig. 4: Parametric S11 analysis on semi-octagonal slot in the ground

RESULTS AND DISCUSSION

The proposed antenna was modelled in ANSYS HFSS electromagnetic simulation software. The antenna's performances were assessed based on its reflection factor (S11), impedance bandwidth, gain, radiation pattern, and surface current distributions. The optimised antenna comprises a radiating patch with an octagonal slot

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loading, incorporated into a semi-octagonal DGS structure, mounted on an FR4 dielectric substrate measuring 30 × 35 × 1.6 mm³.

Reflection Coefficient Analysis

The simulation results for the reflected coefficient (S11) properties of the optimised antenna are illustrated in Fig. 8. The designed antenna exhibits dual-band performance, with resonant frequencies at

6.5 GHz and 10.67 GHz. In the low-frequency range of operation, the designed antenna achieves a return loss of −24.28 dB, indicating good impedance matching. In terms of impedance bandwidth at low operating frequencies, the optimised antenna offers a bandwidth of 2.03 GHz, covering a large part of the microwave spectrum. At the high-frequency band of operation, the optimised antenna shows a resonance frequency of 10.67 GHz, a return loss of −13.03 dB, and a bandwidth of 770 MHz, as depicted in Fig. 5.

Gain Characteristics

The gain of the proposed antenna was evaluated at various frequencies. A gain of 4.0 dBi was obtained at 6.5 GHz, and 4.2 dBi was obtained at 10.67 GHz. The gain does not vary much over the operational frequency band, indicating efficient radiation. This gain enhancement can be attributed to the optimal slot configuration and the modified current distribution induced by the DGS.

Radiation Pattern Analysis

Radiation patterns of the designed antenna at resonance frequencies are shown in Figure 7 below. The antenna demonstrates stable radiation properties with broadside radiation. The radiation patterns in the E-Plane and H-Plane show good symmetry and minimum distortion at resonance frequencies. Based on the radiation properties discussed above, the designed antenna would be useful for both wireless communication and radar applications.

Surface Current Distribution

Simulated current distributions on the surface at 6.5 GHz and 10.67 GHz are illustrated in Fig. 8. From the figure, it is seen that there exist large amounts of current distribution in the region of the inclined rectangular slots and feed section. The contributions of such a current to the generation of the low-frequency resonance mode are quite significant. In the high-frequency resonance mode, the current distributes across both the octagon radiator and the defective ground plane.

Performance Discussion

As shown in the evolution design study, the incorporation of slot loading introduces additional resonant modes and enhances multiband operation. In addition, the use of the semi-octagonal defective ground structure increases the impedance bandwidth by altering the current flow under the radiating patch, as shown in Table 3. The optimised antenna structure, compared to the circular patch antenna, exhibits superior broadband performance while retaining a small size and constant gain. Consequently, the antenna serves as a practical option for X-Band Radar and SatCom Wireless Applications.

Table 3. Performance Summary of the Optimised Antenna

Parameter	**Band 1**	**Band 2**
Resonant Frequency (GHz)	6.5	10.67
Return Loss (dB)	-24.28	-13.03
Bandwidth	2.03 GHz	770 MHz
Gain (dBi)	4.0	4.2

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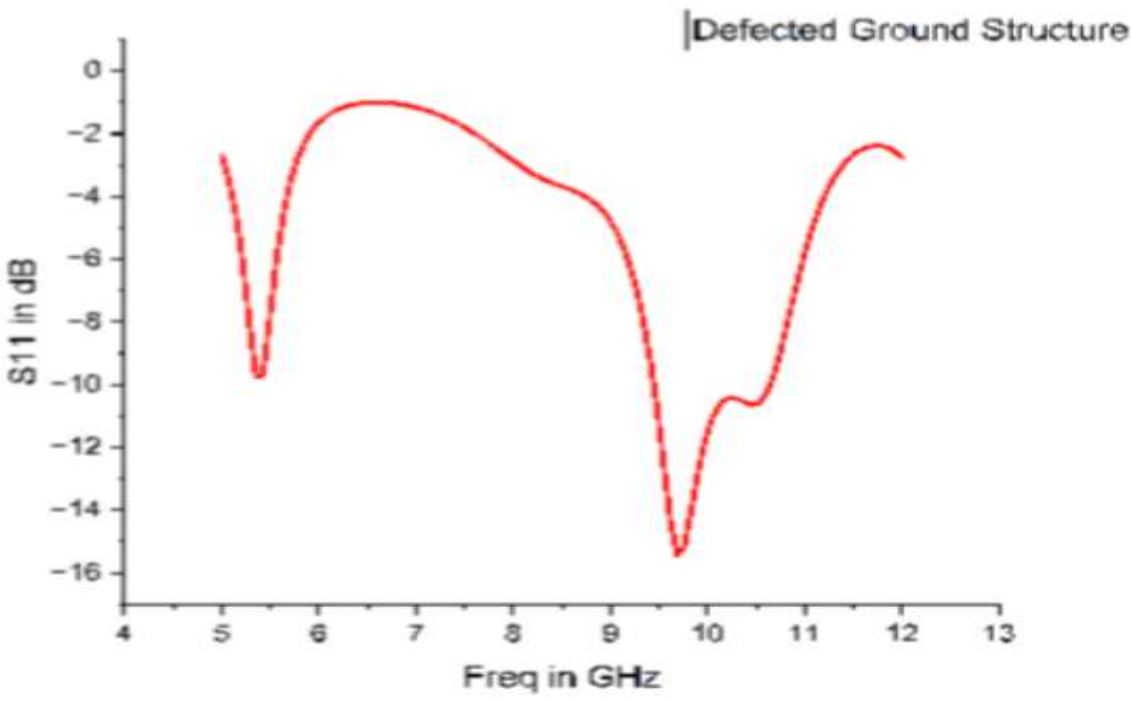
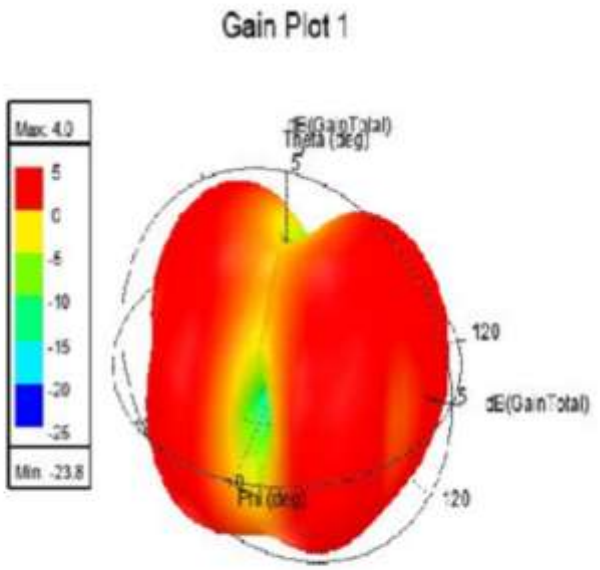
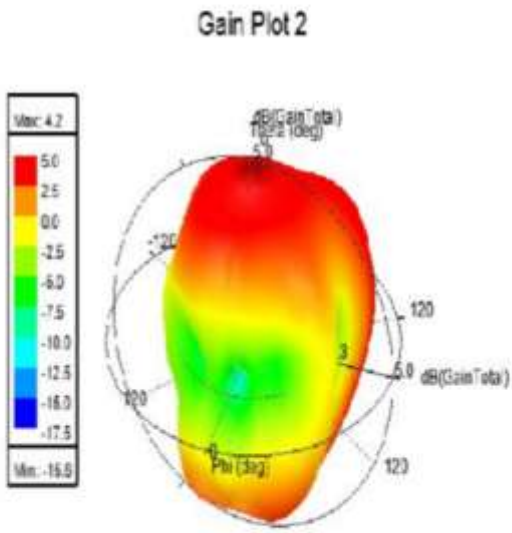


Fig. 5: Simulated S11 characteristics DGS antenna.





(a) (b)

Fig. 6: 3D Gain plots at (a) 6.5 GHz and (b) 10.67 GHz of DGS antenna.

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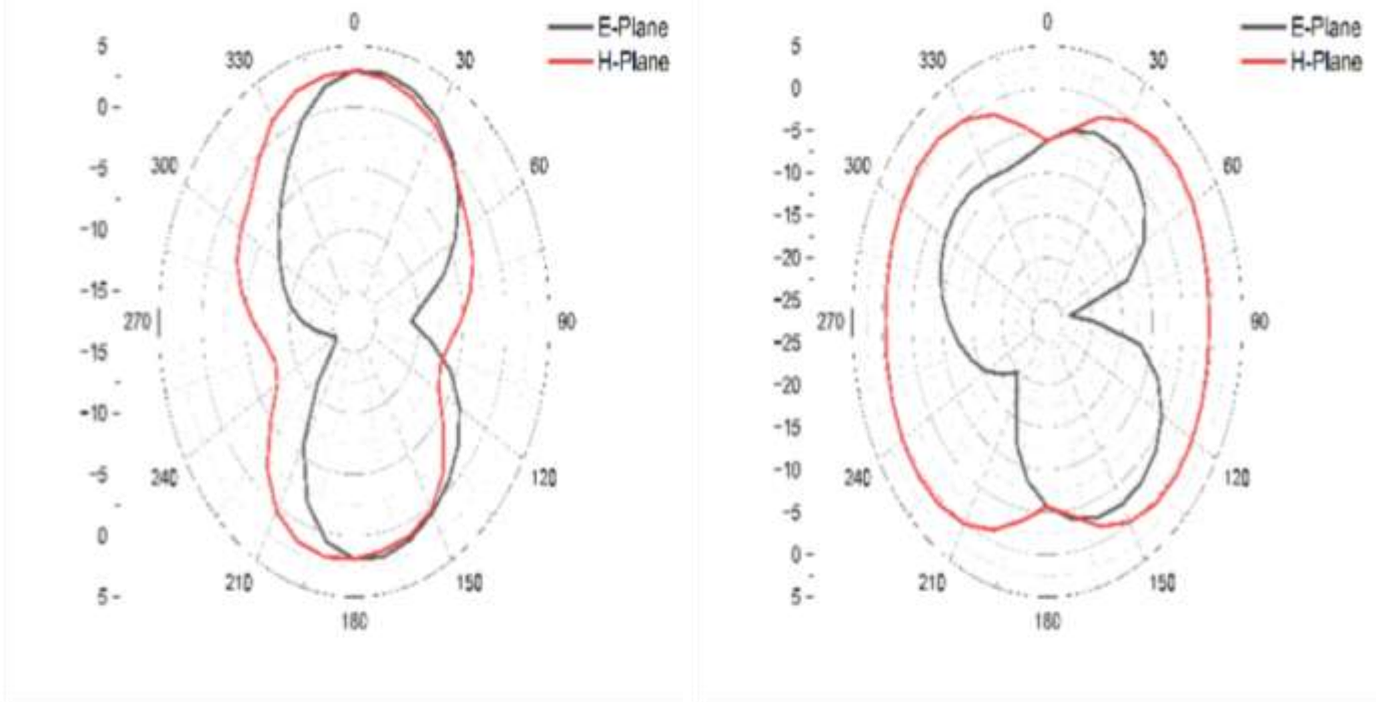
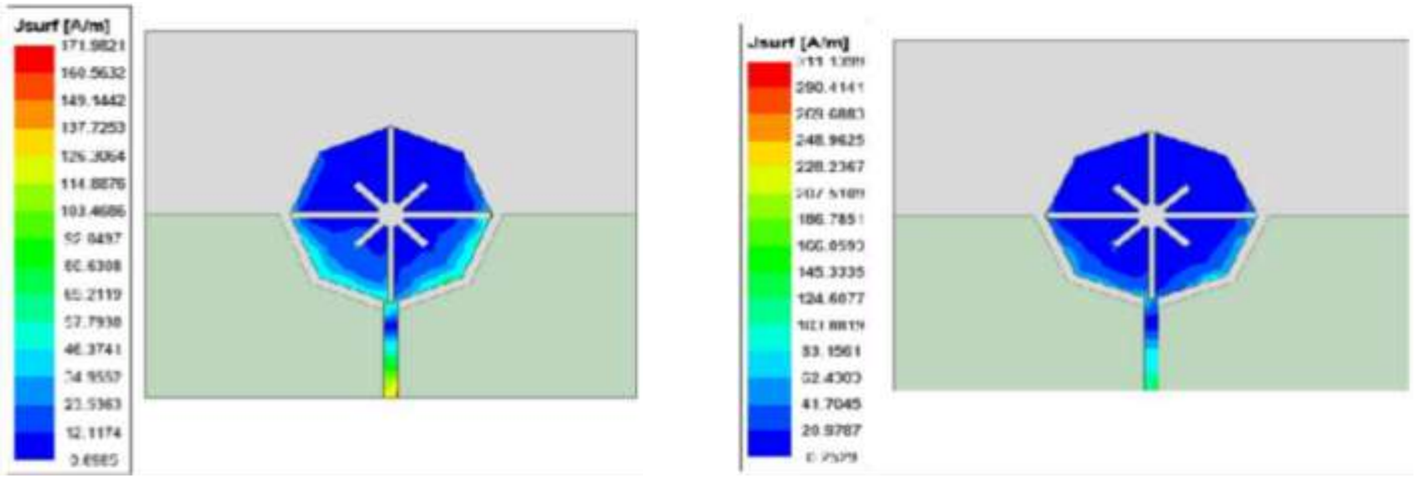


(a) (b)

Fig. 7: E-plane and H-plane radiation patterns at (a) 6.5 GHz and (b) 10.67 GHz of DGS antenna.



(a) (b)

Fig. 8: Surface current distributions at resonant frequencies at (a) 6.5 GHz and (b) 10.67 GHz of DGS antenna.

Comparison with Existing Literature

For the assessment of the proposed antenna, it is compared with various other slot-loaded and defected ground structure (DGS)- based microstrip antennas used in the X-band region. Antenna size, frequency range, bandwidth, gain, and the methods used to improve performance are considered in the comparison. As shown in Table 4, the proposed antenna offers a high bandwidth of 2.03 GHz at a lower operating band, along with very small physical dimensions of 30 × 35 × 1.6 mm³. The antenna also offers dual-band operation with realised gains

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above 4 dBi without using any multi-layered substrates or a feeding network.

The comparison shows that most reported antennas provide either enhanced bandwidth performance or multiband behaviour. However, the proposed antenna design combines slot loading and the semioctagonal DGS technique, providing higher bandwidth and multiband operation. It can be seen that the proposed antenna design evolves from a circular patch to an octagonal slot-loaded radiator. Hence, the proposed design is effective for use in X-band radar applications, satellite communications, and wireless communications.

Table 4. Comparison of the Proposed Antenna with Existing Works

Ref.	**Size (mm^3)**	**Operating Frequencies (GHz)**	**Bandwidth**	**eak Gain (dBi)**
[1]	10 × 10 × 1.6	9.7, 11.4	Moderate	4.5
[2]	40 × 40 × 1.6	10.0	512 MHz	3.8
[3]	40 × 40 × 1.6	10.0	506 MHz	4.0
[4]	40 × 40 mm^2	Multiband	Moderate	5.0
[5]	34 × 47 ×3.27	Broadband	Enhanced	4.2
Proposed Work	30 × 35 × 1.6	6.5, 10.67	2.03 GHz, 770 MHz	4.0, 4.2

CONCLUSION

An octagonal microstrip patch antenna with a slot-loading technique and a semioctagonal defected ground structure is proposed in this paper for wireless communication applications. By using slot loading and an altered ground structure, the antenna bandwidth was significantly increased, along with multiband performance. The designed antenna demonstrated good impedance matching, radiation stability, and high gain efficiency. Due to its simple design and superior performance, it can be used for X-band radar as well as for satellite and other modern wireless communication systems.

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