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A Defected Ground Structure Based Compact Circular Patch Antenna Design for mm-Wave Application

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ABSTRACT

This paper presents a novel defected ground structure-based slotted circular patch antenna for mm-Wave application. A circular patch antenna with a compact size of 10 mm×8 mm×0.75 mm is fabricated in the lab. The designed antenna has a 2 GHz impedance bandwidth that covers the frequency range of 42GHz to 44GHz. It achieves a directional radiation pattern for millimeter-wave applications and has a maximum realized gain of 6 dBi at the operating frequency of 42.65 GHz. Defected ground structure (DGS) is loaded on the bottom of the dielectric substrate, which improves the gain and reduces the surface wave propagation. The proposed antenna has achieved circular polarization which makes it suitable for the mm-Wave application.

Keywords: Circular patch antenna; Circular polarization (CP); Defected ground structure (DGS); Millimeter-wave (mm-Wave)

1. INTRODUCTION

Due to rapid growth in technologies, demand of high speed wireless communication is increasing day by day. Therefore researchers are now attracted towards the high frequency bands to increase the data transfer rate. The millimetre wave band can be a better option for short range high speed wireless communication. The millimetre wave comes under the extremely high frequency (EHF) bands ranging from 30-300 GHz. Its wavelength lies in 1-10 mm range, therefore it is known as millimetre wave. Due to high frequency range and short wavelength, the mm-wave can be used in short range radar communication, satellite communication, 5G telecommunications, Wireless Personal Area Network (WPAN), high quality videos, body scanners at airports etc.[1]

For any wireless communication, antenna is the key element. The design of antenna for portable and wireless devices with high speed data rate is a challenging task for the antenna designers to fulfil all the requirements. These days, patch antenna is being used for high speed portable wireless devices due to its simple design, compactness, low cost and easy fabrication. They can be easily integrated with other microwave circuits. The main disadvantages of traditional patch antenna are narrows band width and low efficiency.[2] Since mm-wave applications include wide frequency band and high speed wireless communication therefore there is need of improvement in band width and efficiency of patch antenna. Recently, many techniques have been used to improve fundamental characteristics of the conventional patch antennas. Several method to increase the fundamental charecterstics of antenna have been proposed in literature. Some of them are using different feeding techniques, multiple substrate loading, Frequency Selective Surface, Electromagnetic Band Gap structure, and metamaterial. These approaches enhance the fundamental charecterstics of the antenna. Some techniques like − defected ground structure (DGS), coplanar waveguide (CPW), and substrate integrated waveguide (SIW) are used for improvement in bandwidth and efficiency of patch antenna.[3-4]

In[5] an L-slotted antenna based on DGS is designed for mm-wave applications. By using defected ground structure, bandwidth, efficiency and VSWR of antenna was improved. The designed antenna covers the 5G band, ranging from 41-42.5 GHz. A dual band DGS based rectangular patch antenna is designed in[6] for 5G mm-wave applications. The designed antenna shows compact volume of $(8\times8\times0.8)$ mm^3 and resonates at 28 and 42 GHz frequency band. In this paper improvement in the gain is observed due to loading of DGS structure. In,[7] a DGS based mm-Wave antenna is designed for mm-Wave applications. The fabricated prototype consists of rectangular patch at FR-4 substrate with total volume of $5\times5\times0.8$ mm^3. The designed antenna covers the mm-wave frequency range and Q-band from 30 to 40 GHz. The designed antenna shows good bandwidth, gain and efficiency. A shorted patch SIW fed, patch antenna is proposed in[8] for Q-band applications. Three metallic posts are used to connect the ground and patch, due to which the bandwidth of the designed antenna is enhanced by 22.2 % in the operating frequency from 40 to 50 GHz. In[9] a high gain (6 dBi) beam steering array antenna at the resonant frequency of 28 GHz is proposed to overcome the path loss effect in mm-wave applications.

This paper proposed a slotted circular microstrip patch antenna design based on DGS ground plane for mm-wave

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applications. This paper is divided into four sections. The first section describes the introduction and literature survey on DGS based patch antenna for mm-wave applications. The design specifications and results analysis are presented in section two and three respectively. In the last, the conclusion is given in the fourth section.

2. DESIGN AND SPECIFICATIONS

This section presents, the design specifications of slotted circular patch antenna based on defected ground structure. The simulated and fabricated prototype of the slotted circular patch antenna is shown in Fig. 1 and Fig. 2 respectivily. It is fabricated on the dielectric substrate of Arlon AD320A with

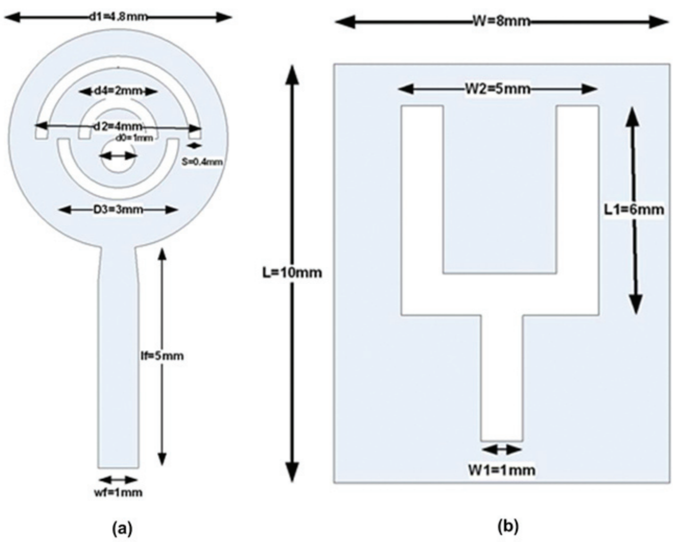


Figure 1. Simulated view of designed antenna: (a) Top view and (b) Bottom view

Figure 2. Fabricated prototype of designed antenna: (a) Top view and (b) Bottom view

relative permitivity ($\varepsilon_r \varepsilon_r$) of 3.2 and loss tangent of 0.0032. The height of the dielectric substrate is 0.75 mm. The simulated view of top and bottom of the proposed antenna is shown in Fig. 1(a) and Fig. 1(b) respectively.

HFSS v18 simulation software is used for designing the antenna. In the bottom of dielectric substrate, a tuning fork shaped defected ground structure is used to increase the bandwidth, gain, and mutual coupling and minimize the cross-polarization interference and propagation of surface wave on the dielectric substrate. The defected ground structure changes the current path circulation on the ground plane. This current path change shows the variation in the characteristics of a tapered microstrip line by including capacitance, inductance, and resistance which can lead to a shift in resonant frequency. In the bottom of the dielectric substrate, a tuning fork-shaped slotted structure is loaded, as shown in Fig. 1(b). A tapered microstrip line with a 50 ohms SMA connector is used to feed RF power. Due to the tapered microstrip line with the radiating patch, a good impedance matching has been achieved which is shown in Fig. 1(a). Systematically reducing and periodically arranged Arc-shaped slots are etched out from the circular patch. This set of slots help in reducing the size and achieving good impedance matching with the defected ground plane. The optimized dimension of the designed antenna is 10 mm× 8 mm×0.75 mm.

The fabricated top and bottom views of the antenna prototype are illustrated in Fig. 2(a) and Fig. 2(b) respectively. The optimized parameters of the designed antenna are given in Table 1.

Table 1. Dimension of the antenna (in mm)

Parameter	L	W	l	W1	W2	d0	d1	d2
Value	10	8	6	1	5	1	4.8	3.6
parameter	d3	d4	S	lf	wf	h		
Value	2.8	2	0.4	5	1	0.75		

3. RESULTS AND DISCUSSION

The proposed design of antenna is shown in Fig. 3. Some optimization steps to reach the final geometry are also shown. Initially, a conventional circular patch antenna is designed on a ground plane and S_{11} (dB) is observed. It has resonant frequency of 43.65 GHz due to poor impedance matching. In the second step, tapering of the microstrip line has been done for better impedance matching with a circular patch. But the S_{11} (dB) graph does not show good impedance matching in desired frequency band. Therefore, in the third step, a semicircular ring slot has been removed from the radiating patch. In the fourth step, another ring slot is cut from the patch as shown in Fig. 3. In this stage, good impedance matching has been observed. But the resonant frequency shifted from 42.65 GHz to 43.55 GHz. In the fifth step, another ring slot is removed from the circular patch. Now it is observed that the S_{11} (dB) graph has 42.75 GHz resonant frequency. In the sixth step, another circular slot is cut from the patch, which shifts the S_{11} (dB) graph at 42.5 GHz resonant frequency. In the final step, a tuning fork-shaped slot is cut from the ground plane for achieving good impedance matching in the desired frequency band as shown in Fig. 4.

After loading DGS on the ground plane with a slotted circular patch and tapered microstrip line, bandwidth is enhanced, and suitable impedance matching is observed. The simulated and measured S_{11}(dB) parameter of the designed antenna is illustrated in Fig. 4. It is shown that the simulated and measured graph of the designed antenna matched very well over the same frequency range. The simulated result of bandwidth of designed antenna (below -10dB level) is from 42.25 GHz to 43.5 GHz at operating frequency of 42.5 GHz. The fabricated patch antenna has achieved a bandwidth of 2 GHz from 42GHz to 44GHz with a resonant frequency of 42.65GHz.

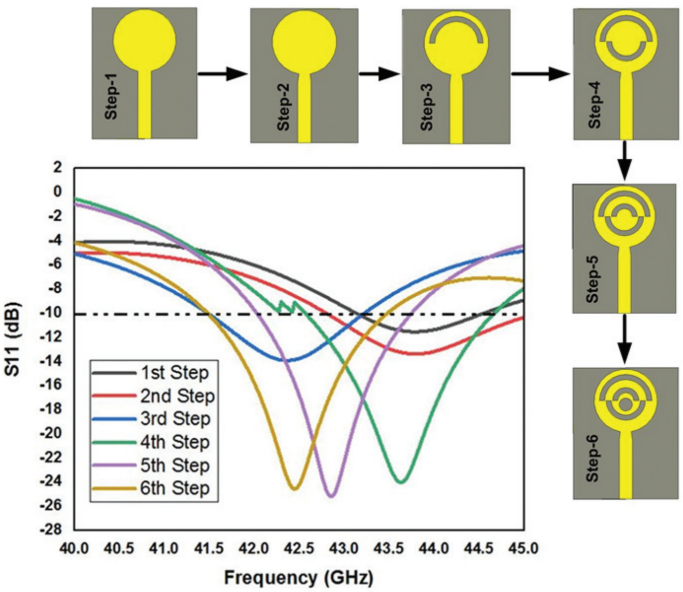


Figure 3. Simulated S_{11} (dB) with optimization steps.

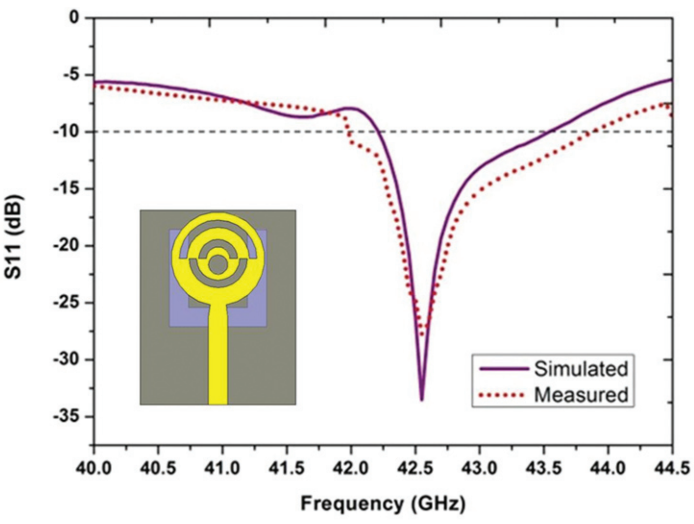


Figure 4. Measured and simulated S_{11} (dB) with the loading of defected ground structure.

Initially, the patch antenna without loading of defected ground plane is simulated in the HFSS tool. Without loading of DGS, the simulated and measured graph of reflection coefficient S_{11} (dB) is illustrated in Fig. 5. The simulated and measured S_{11} (dB) graph has very poor impedance matching with a frequency range from 41.8 GHz to 43.1 GHz and from 41.8 GHz to 42.75 GHz respectively.

For optimization of antenna design, a parametric analysis with the variation of radius r_x of a circular slot is shown in Fig. 6. It shows that a radius (r_x) of 0.5mm circular slot achieved good impedance matching with desired frequency range at 42.65 GHz resonant frequency. The proposed antenna has peak gain results with respect to frequency which is shown in Fig. 7. The simulated and measured realized gain of 6.5 dBi and 6 dBi has been achieved at operating frequencies of 42.5 GHz and 42.65 GHz, respectively. The surface current density on the radiating patch at operating frequency of 42.5 GHz is shown in Fig. 8. Due to slots cut from the circular patch and tapered microstrip line along with the defected ground plane, the radiating patch has a maximum magnitude of current at the edges and tapered microstrip line. The surface current (J_{surf}) distribution on the radiating patch depends on the substrate height which is responsible for the miniaturization of the antenna. It can be observed that less thickness of substrate enhances the radiation efficiency in far-field and minimize the surface radiation from the substrate.

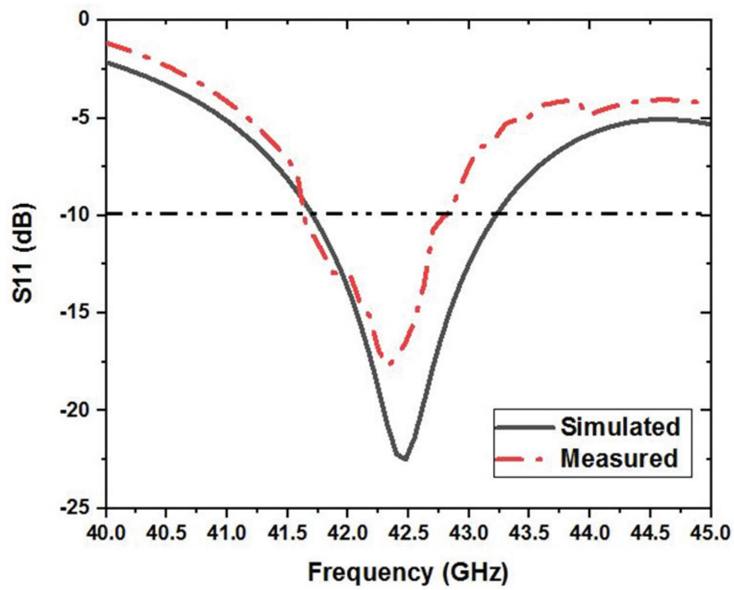


Figure 5. Measured and simulated S_{11} (dB) without loading of defected ground structure.

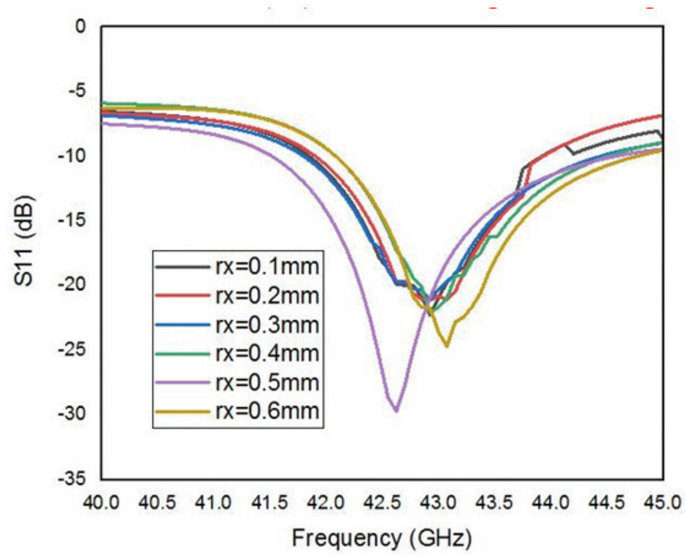


Figure 6. Simulated S_{11} (dB) with the variation of radius (r_x= 0.1mm to 0.6mm) of circular slot cut from pach.

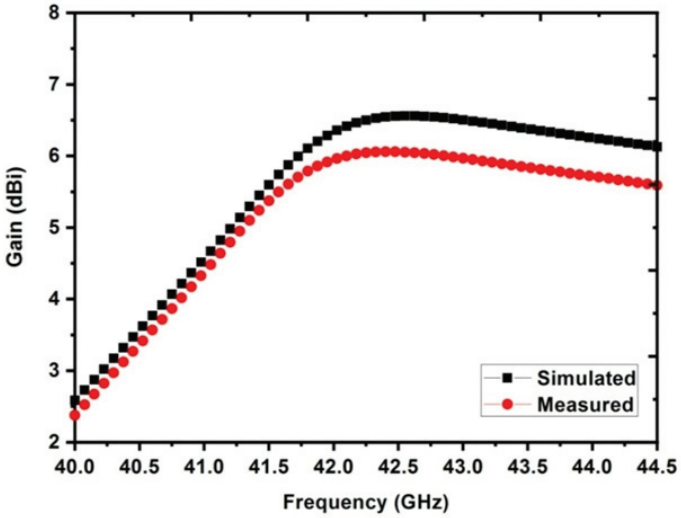


Figure 7. Measured and simulated gain of proposed antenna.

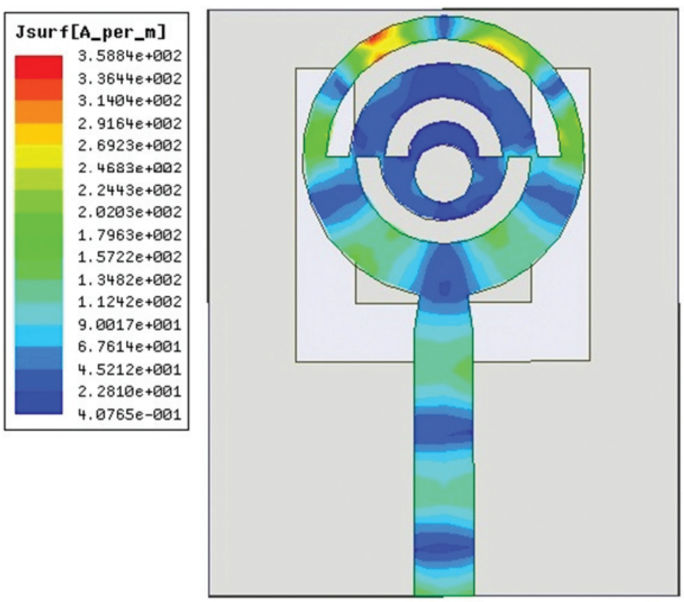


Figure 8. Surface current density on radiating patch.

The simulated and measured antenna has an axial ratio below 3dB that covers the range from 42.25 GHz to 44 GHz and from 42.25 GHz to 43.75 GHz respectivily. It implies that the designed antenna is circularly polarized, as illustrated in Fig. 9. It can radiate EM waves in the horizontal and vertical planes as well as in every plane required for the receiver side of the antenna to receive all transmitted data from the transmitter antenna. Cross polarization interference is minimized in a circularly polarized antenna that can be used in the higher frequency range. The proposed antenna, which is circularly polarized, can be used in the mm-Wave application.

The simulated and measured far-field radiation patterns in each of the planes is shown in Fig. 10. It shows the H-plane $(\varphi=90^o)$and E-plane $(\varphi=0^0)$of the proposed antenna at 42.5 GHz resonant frequency. It can be shown that the designed antenna has nearly a bi-directional radiation pattern in the H-plane and a directional pattern in the E-plane. The current density is distributed randomly on the radiating patch that introduces the electromagnetic interference at higher frequencies. A defected ground plane is loaded, which suppresses the surface wave on the dielectric substrate to overcome these interferences.

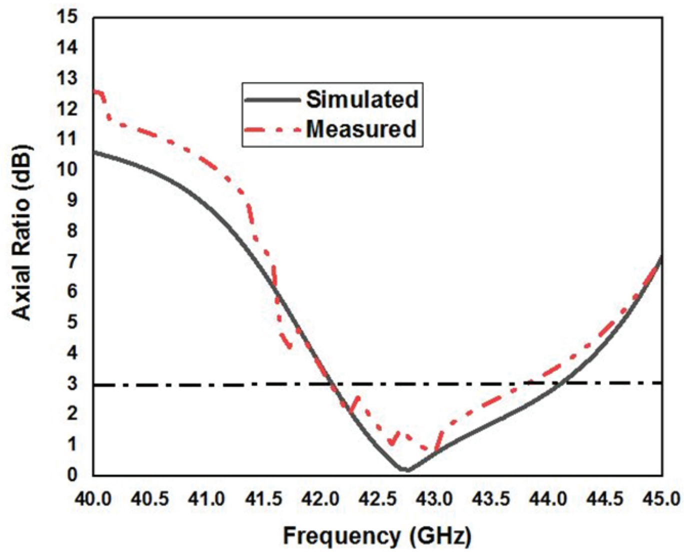


Figure 9. Simulated and measured axial ratio of the proposed antenna.

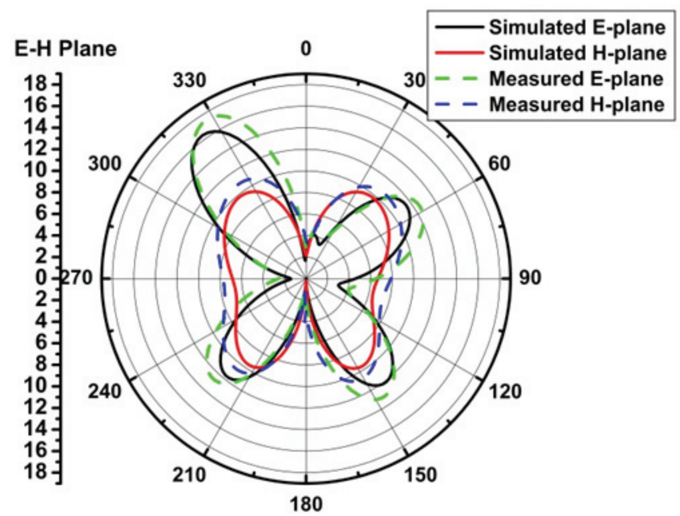


Figure 10. Simulated and measured radiation pattern of E-H plane.

The orientation of E-H plane in a particular direction is known as polarization. It is classified into two types of polarization. The first one is co-polarization which is useful polarization, and the second one is cross-polarization which is undesired. The simulated and measured Co-cross polarization in the E-H plane are shown in Fig. 11(a) and 11(b), respectively. Figure 11(a) shows E-plane with a maximum co-polarization magnitude. The cross-polarization increases in the E-plane at a certain magnitude with higher frequencies due to a wide radiation area. Figure 11(b) shows H-plane with an omnidirectional pattern and low cross-polarization magnitude. The cross-polarization is less than -10dB in H-plane, which is desired for radiation purposes in wireless communication for mm-Wave applications.

A measurement setup is shown in Fig. 12. In this Fig. the

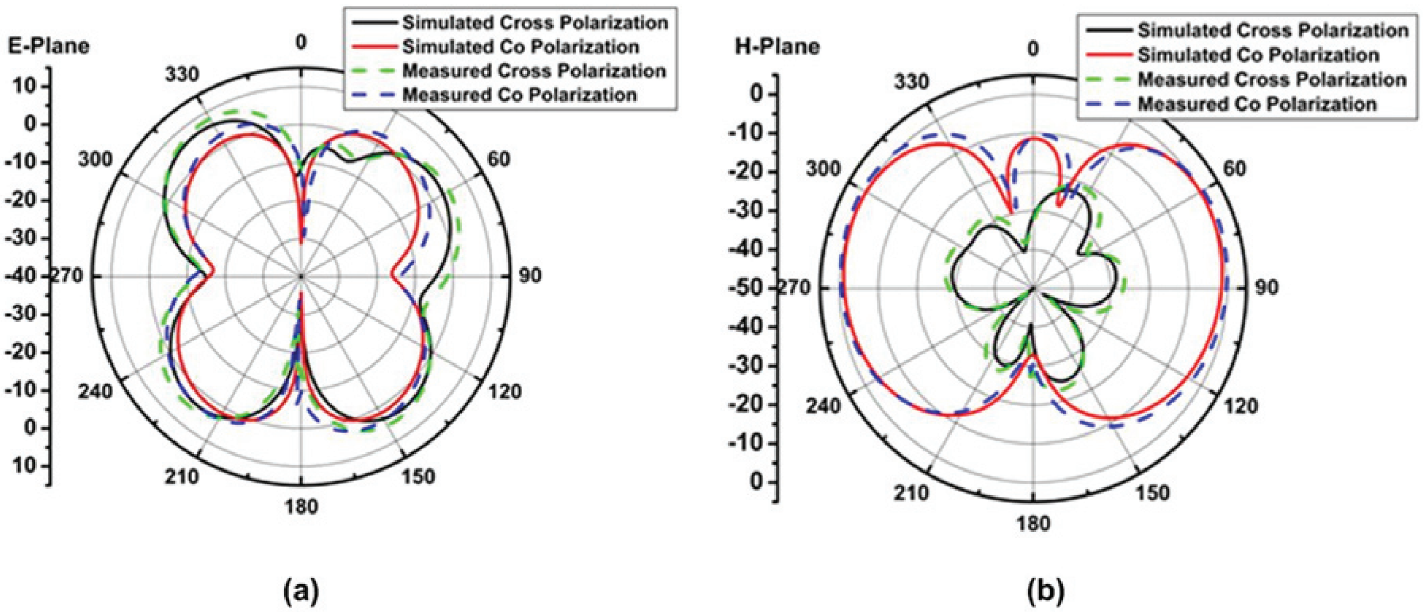


Figure 11. Simulated and measured Co-cross polarization of antenna (a) E-plane co-cross polarization (b) H-plane co-cross polarization.

Figure 12. Measurement setup of proposed antenna design.

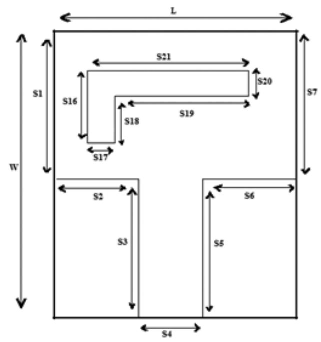
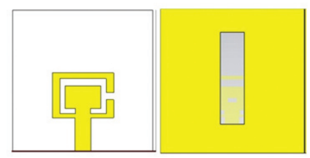
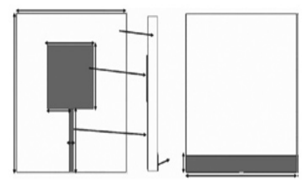
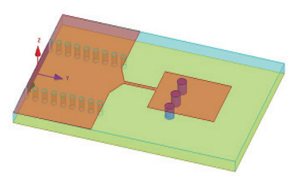
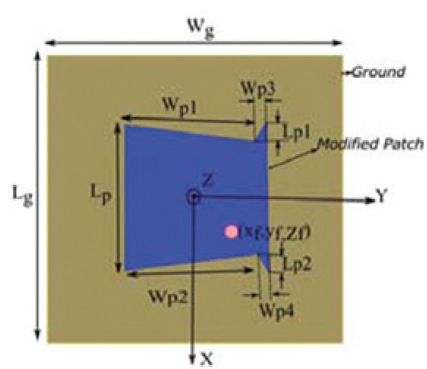
fabricated antenna is connected through a cable which is placed in an anechoic chamber for measurement of far-field radiation. For S_{11} (dB), and VSWR graph measurement the fabricated antenna is connected with a vector network analyzer through a cable which is shown in Fig. 12.

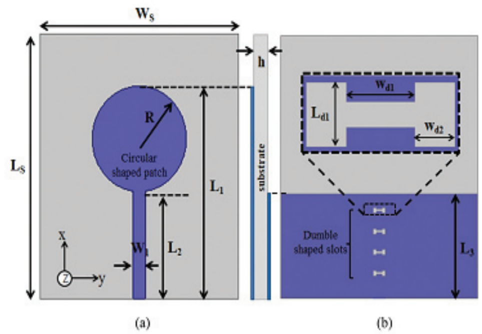
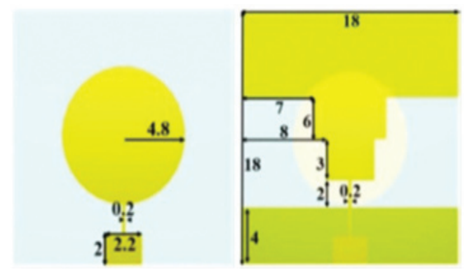
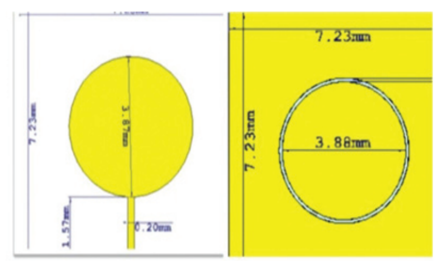
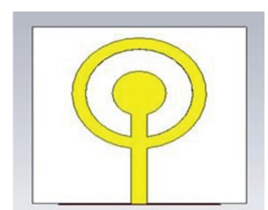
Finally, the comparison between the designed antenna with other references is shown in Table 2. It shows that the designed DGS based circular patch antenna has better results than the reference paper.

4. CONCLUSION

This paper presents, a defected ground plane with slotted circular microstrip patch antenna. It has a compact volume of (10×8×0.75) mm^3. The proposed antenna works at 42.65 GHz and achieves 6 dBi of gain and a directional radiation pattern. The surface current density on the dielectric substrate is minimized due to the loading of the defected ground plane. The designed antenna has circular polarization with a range of 42.25 GHz to 44 GHz. It has minimum cross polarization interference which is desired for wireless communication. The designed antenna can be used for high speed wireless communication and satellite communication in mm-Wave range.

Table 2. Comparison of the parameters of proposed work with other reference papers.

Ref.	Size (mm^2)	Resonant Frequency (GHz)	Bandwidth (GHz)	Peak Gain (dBi)	Axial ratio (%)	Geometry of antenna
5	3×2.5	42	1.5	3	No CP	
6	8×8	28.2/42	2	6.12/6.21	No CP	
7	5×5	44.5	1.5	N.A.	No CP	
8	5×5	44	10	3	No CP	
9	5.8×5.8	28	5.12	6.9	No CP	

10	48×38	2.9 and 9.1	8.1	8.4 and 8.2	3.2% at 9.1 GHz (Circular Polarization)	
11	60×60	3.6	0.4	2.41	No CP	
12	7.23×7.23	28 and 38	0.87 and 1.07	6.87 and 4.17	No CP	
13	8×8	41.08, 47.4, and 54.4	0.150, 0.222 and 0.219	6.16, 9.89 and 5.54	No CP	
Proposed work	10×8	42.65	2	6 dBi	4.1 % (Circular Polarization)	

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He has contributed to the introduction part of the literature survey on mm-wave applications.

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He has provided technical inputs and suggestions to improve the design and write-up of the manuscript.