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Design and Analysis of Compact Periodic Slot Multiband Antenna with Defected Ground Structure for Wireless Applications

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Abstract—A novel compact patch antenna with Defected Ground structure (DGS) operating for Wireless applications is proposed and investigated. This proposed antenna generates four separate resonances to cover 3.271 GHz (WiMax), 4.92 GHz (WiFi), 6.35 GHz (Space applications), and 11.04 GHz (Fixed Satellite applications) while maintaining overall compact size of $32 \times 32 \times 1.6\,\mathrm{mm}^3$ using an FR-4 substrate commonly available with a permittivity of $\varepsilon_r = 4.4$. The proposed microstrip patch antenna (MSPA) consists of a square radiator in which a periodic slot is etched out along with square defects on ground surface and a microstrip feed line. The periodic slot with DGS modifies the total current path thereby making the antenna operate at five useful bands. Structure displays the impedance bandwidth of 8.34% (3.10–3.37 GHz), 2.00% (4.88–4.98 GHz), 14.68% (6.27–7.194 GHz), and 5.41% (10.79–11.39 GHz) with gains 3.25 dB, 2.45 dB, 5.65 dB, and 4.47 dB, respectively. The antenna performance is analyzed using numerous parametric optimization studies, field distributions, and currents. Excellent agreement is obtained between measured and simulated results.

1. INTRODUCTION

In view of the ever-increasing demand for high data rate, the need for wide band antenna in communication systems also increases simultaneously. This facilitates the transmission of large volumes of data with a short time. By the integration of several structures on the same substrate we can design an antenna that can operate over a wide range of frequencies. The design of a microstrip patch antenna has become a challenge for designers in mobile wireless communication systems with enhanced features. Much research is underway to develop structures that can meet the desired needs [1–6]. MSPAs are designed by various feeding techniques such as coaxial probe, microstrip line, aperture coupling, and proximity coupling. A frequently used feeding technique is microstrip line because of the ease of fabrication and integration. The most important part of an MSPA is the ground plane, and the radiation emerging between ground and the patch is due to the fringing effect between ground and the patch [7].

Antenna patches may be of different shapes such as circle, square, ring, triangle, polygon, hexagon, and octagon [8–12]. The introduction of slot/slots on the radiating surface can make the antenna resonate at multiple bands. In addition, in order to improve the impedance bandwidth of the patch antenna, various forms of defects are introduced at the surface of the ground, described by various authors [13, 14]. Subsequent introduction of various slot/slots on the patch as well as defects on the ground surface can also improve bandwidth and gain [15–17]. The performance of different multiband antennas is reported by several authors with impedance bandwidth and gain characteristics with various structures using DGS [18–25]. DGS is a concept which is used to improve the impedance bandwidth of an antenna as well as to explore additional resonance frequencies.

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In this paper, a new compact patch antenna is proposed with a defect on the ground surface which resonates at 3.71 GHz, 4.92 GHz, 6.35 GHz, and 11.04 GHz and is suitable for various wireless and satellite applications with good gain and impedance bandwidth.

2. PROPOSED ANTENNA DESIGN

Geometries of the proposed rectangular slit patch antenna with and without DGS are shown in Fig. 1. The length and width of the proposed antenna are 32 mm × 32 mm. For this design, the radiating patch and ground plane are etched on either side of a most commonly available FR4 substrate having dielectric constant $\varepsilon_r = 4.4$, loss tangent 0.02, and substrate thickness 1.6 mm. The simulation is carried out using licensed electromagnetic solver high frequency structure simulator (HFSS) software. The recursive process of designing the proposed antenna is carried out by changing iteration 1 to iteration 4 to obtain high impedance bandwidth which is shown in Fig. 2.

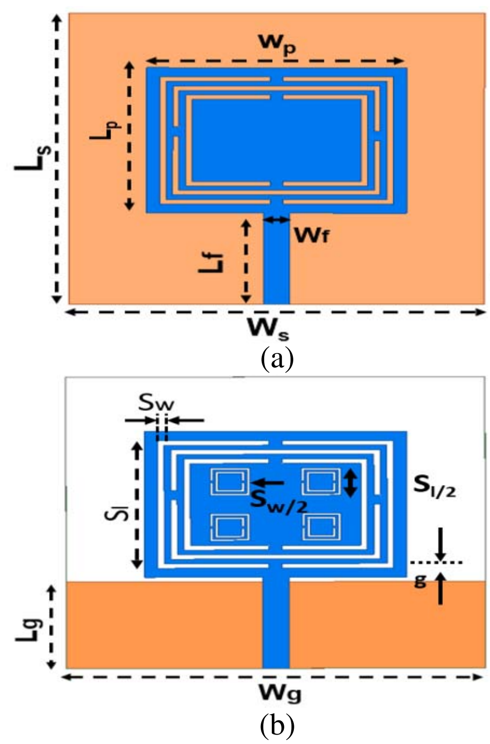


Figure 1. Schematic configuration of (a) antenna without DGS, (b) antenna with DGS.

The width and length of the basic rectangular patch antenna iteration 1 can be calculated by the following design equations [22]

$$W = \frac{C}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

where W is the width of patch antenna, f_r the resonant frequency, ε_r the relative permittivity, and C the Velocity of Light

$$L = \frac{c}{2f_r\sqrt{\varepsilon_e}} - 2\Delta L, \tag{2}$$

where ε_e is the effective relative permittivity, and ΔL is the effective length

$$\varepsilon_e = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\left[1 + \frac{12h}{W}\right]^{-1/2} \tag{3}$$

where h is the height of substrate

$$\Delta L = \frac{0.412h(\varepsilon_e + 0.3)\left(W/_h + 0.264\right)}{(\varepsilon_e - 0.258)\left(W/_h + 0.8\right)} \tag{4}$$

Based on the above equations, the lengths and widths of basic patch antenna are calculated operating at 4 GHz, and further modification on patch and removing some portions on ground more resonant frequency will be performed. Various dimensions of the proposed antenna are indicated in Table 1.

Table 1. Notations of various parameters of proposed antenna.

Parameter	Notation	Dimension (mm)
Substrate Length	L_s	32
Substrate Width	W_s	32
Ground Length (DGS)	L_g	9.5
Ground Width (DGS)	W_g	32
Length of Patch	L_p	16
Width of Patch	W_p	20
Length of Strip	L_f	10
Width of Strip	W_f	2
Spacing between slits	S_l	0.5
Slot Width	S_w	0.5

3. ANTENNA RESULTS AND DISCUSSIONS

3.1. Parametric Analysis

The parametric study is used to analyze the proposed antenna with improved impedance bandwidth and gain. The variability of W_F strip feed width, various DGS shapes, and the use of various substrates is used to evaluate the performance of the proposed antenna for various parametric values. All the parametric analysis results are indicated in Table 2.

3.1.1. Return Loss Variation with Design Iterations

Parametric analysis is carried out for different iterations of the patch antenna as shown in Fig. 2. Based on Equations (1)–(4) producing the basic rectangular patch antenna was presented in iteration 1 operating at 4 GHz. Iteration 2 is produced by placing a 3 split rectangular type of periodic slots

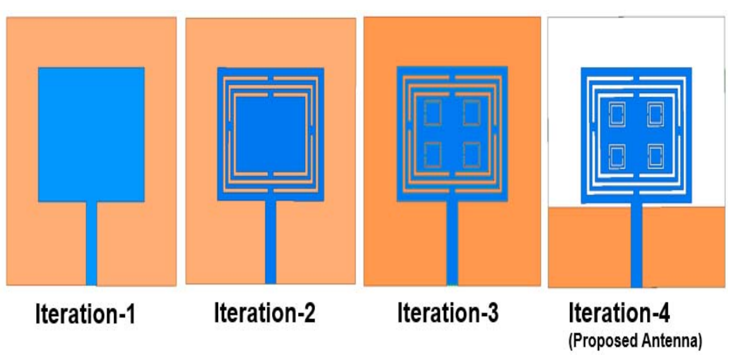


Figure 2. Schematic configuration of design iterations ((1), (2), (3) and (4)).

Table 2. Parametric performance analysis of various parameters variation.

Parameter Variation		Frequency bands (GHz)	Impedance Bandwidth (%)	Gain in dB
Iteration	1	4	3.30	2
	2	7.34, 12.13, 13.84	2.17, 1.07, 6.21	1.6, 2.1, 0.8
	3	7.78, 11.88, 13.28	3.77, 1.93, 4.48	2.3, 2, 1.3
	4	**3.27, 4.92, 6.35, 11.04**	**8.34, 2.0, 14.68, 5.41**	**3.25, 2.45, 5.65, 4.47**
Gap g (mm)	**0.5**	**3.27, 4.92, 6.35, 11.04**	**8.34, 2.0, 14.68, 5.41**	**3.25, 2.45, 5.65, 4.47**
	1.5	3.17, 4.92, 8.31, 10.33, 12.07	1.57, 8.94, 0.36, 5.373, 19.826	2.4, 1.5, 2.1, 0.9, 1.09
	−0.5	3.33, 4.88, 6.35, 8.43, 11.14	6.6, 1.22, 12.9, 27.127, 2.238	1.1, 2.02, 1.7, 1.9
Width of Strip feed W_f (mm)	1	7.4, 12.13, 13.84	0.5, 0.71, 6	1.2, 1.7, 2.3
	2	**3.27, 4.92, 6.35, 11.04**	**8.34, 2.0, 14.68, 5.41**	**3.25, 2.45, 5.65, 4.47**
	3	2.74, 7.16, 8.12, 8.40	2.74, 4.20, 4.14, 1.895	2.41, 0.54, 1.27
Teflon	$\varepsilon_r = 2.1$	7.41, 10.06, 12.4	12.81, 3.4, 4.22	1.22, 0.98, 1.83
RT Duroid	$\varepsilon_r = 2.2$	2.89, 10.9	0.5, 0.9	0.56, 0.91
FR 4	$\boldsymbol{\varepsilon_r = 4.4}$	**3.27, 4.92, 6.35, 11.04**	**8.34, 2.0, 14.68, 5.41**	**3.25, 2.45, 5.65, 4.47**
Without DGS		7.78, 11.88, 13.28	3.77, 1.93, 4.48	2.01, 0.94, 1.37
With DGS		**3.27, 4.92, 6.35, 11.04**	**8.34, 2.0, 14.68, 5.41**	**3.25, 2.45, 5.65, 4.47**

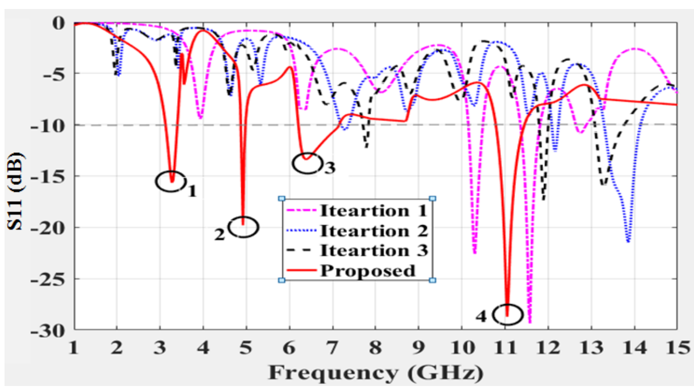


Figure 3. Simulated return loss of design iterations (1, 2, 3, and 4).

on a radiating patch structure, which are orthogonal to each other operating at 7.34 GHz, 12.13 GHz, and 13.84 GHz. Iteration 3 is obtained by introducing another 3 split rectangular type of periodic slots on the radiating patch structure, which are orthogonal with reduced size operating at 7.78 GHz, 11.88 GHz, and 13.28 GHz. Finally, iteration 4 is obtained by etching some portion on ground namely DGS operating at 3.27 GHz, 4.92 GHz, 6.35 GHz, and 11.04 GHz. Comparative variations of return loss by the loss of return for design iterations (1), (2), (3), and (4) are illustrated in Fig. 3. A significant increase in the number of operating bands has been observed from one iteration to the next.

3.1.2. Return Loss Curves with and without DGS

Parametric analysis is performed with and without DGS, as shown in Fig. 4. An increase in the impedance bandwidth of operating bands was observed due to the introduction of DGS into the proposed antenna. Simulated results are shown in Fig. 5. From Fig. 5 it is clear that patch antenna without DGS operates at only 3 bands where a patch antenna with DGS operates at 4 frequencies with improved impedance bandwidth. It is also clear that without DGS the first operating frequency is at 7.78 GHz, and with DGS the the first operating frequency is at 3.27 GHz without increase in antenna size where the frequency is inversely proportional size of antenna validating frequency shifting property.

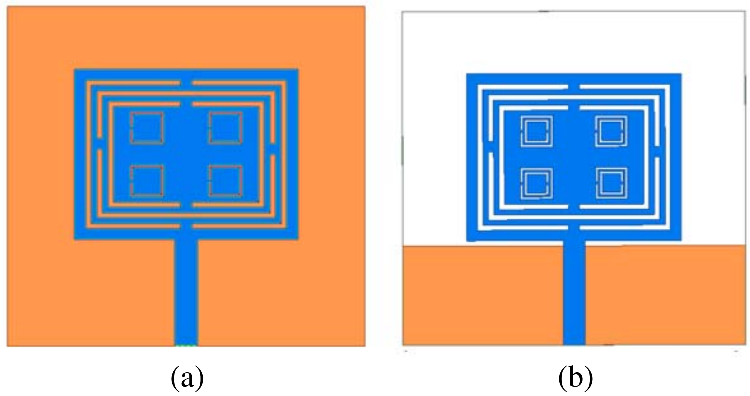


Figure 4. Schematic configuration of (a) antenna without DGS, (b) antenna with DGS.

3.1.3. Return Loss Curve for Various Substrates

The parametric variations of proposed structure with various substrates are simulated namely with FR4 ($\varepsilon_r = 4.4$), RT Duroid ($\varepsilon_r = 2.2$), and Teflon ($\varepsilon_r = 2$) shown in Fig. 6. FR4 substrate exhibits comparatively better performance than RT Duroid and Teflon. Using RT Duroid substrate the patch antenna operates at only 2 bands, and Teflon substrate operates only at 3 bands.

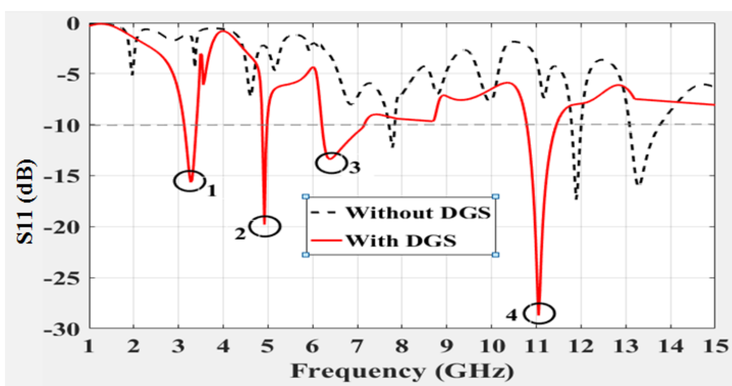


Figure 5. Simulated return loss with and without DGS.

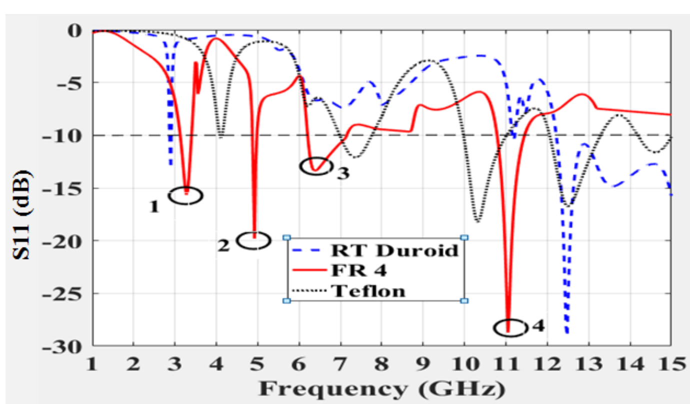


Figure 6. Simulated return loss curves for various substrates.

3.1.4. Return Loss Curve Variation for Various DGSs

The parametric analysis is performed by changing various DGSs as shown in Fig. 7, and the return loss curves for various DGSs are shown in Fig. 8. It is clear from Fig. 8 that using a parabolic DGS, the patch antenna operates at 3 bands namely at 7 GHz, 10 GHz, and 11.9 GHz; using an H-shape DGS, the patch antenna operates at 3 bands namely 4.8 GHz, 7.8 GHz, and 14 GHz while using the proposed DGS, the patch antenna operates at 4 bands namely 3.27 GHz, 4.92 GHz, 6.35 GHz, and 11.04 GHz.

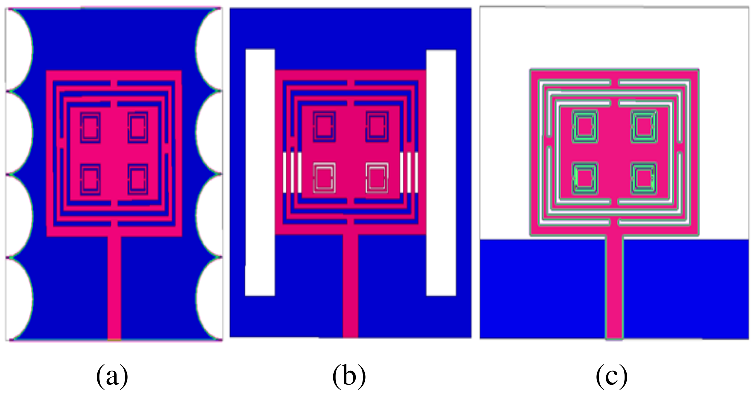


Figure 7. Different DGS (a) parabolic, (b) H shape and (c) proposed.

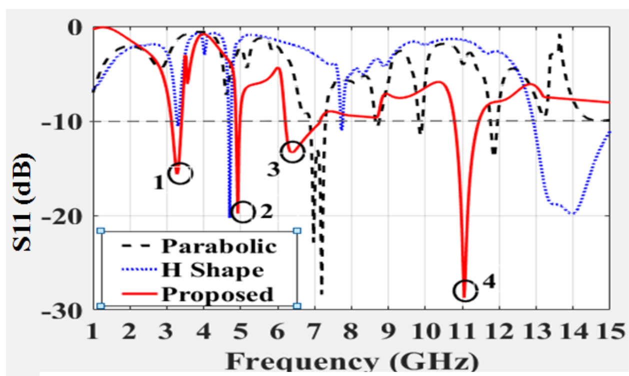


Figure 8. Simulated return loss curves for various substrates.

3.1.5. Return Loss Curve Variation for Strip Feed width W_f

The parametric analysis is performed by varying the width of feed strip W_f for different widths, namely 1 mm, 2 mm, and 3 mm, which is illustrated in Fig. 9. Optimized results are observed for strip feed $W_f = 2$ mm. It is noticed from Fig. 9 that for strip widths $W_f = 1$ mm and $W_f = 3$ mm the antenna resonates at 3 bands only, and for strip width $W_f = 2$ mm the patch antenna resonates at 4 bands namely 3.27 GHz, 4.92 GHz, 6.35 GHz, and 11.04 GHz.

3.2. VSWR

The mismatch power between antenna and feed line has been defined by the VSWR of any antenna. The VSWR plot of simulated proposed antenna is shown in Fig. 10.

3.3. Gain

The simulated gain in dB for the proposed antenna design is shown in Fig. 11. It can be seen that the gains achieved at frequencies 3.27 GHz, 4.92 GHz, 6.35 GHz, and 11.04 GHz are 3.25 dB, 2.45 dB, 5.65 dB, and 4.47 dB, respectively.

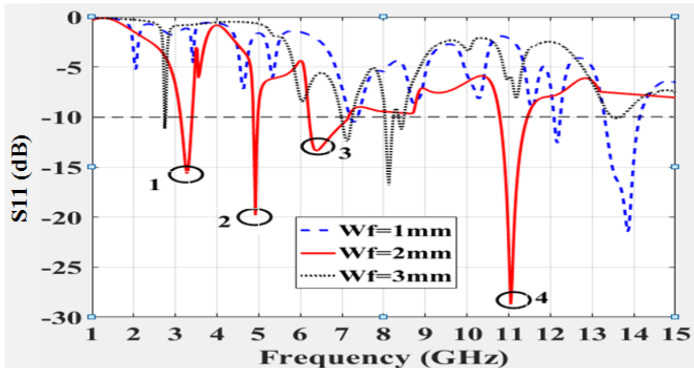


Figure 9. Simulated return loss curves for various values of W_f.

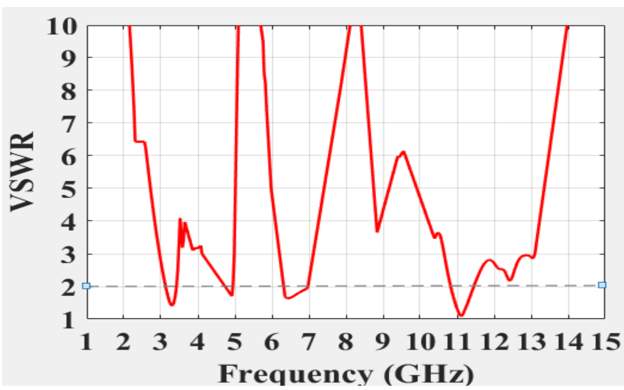


Figure 10. Simulated VSWR.

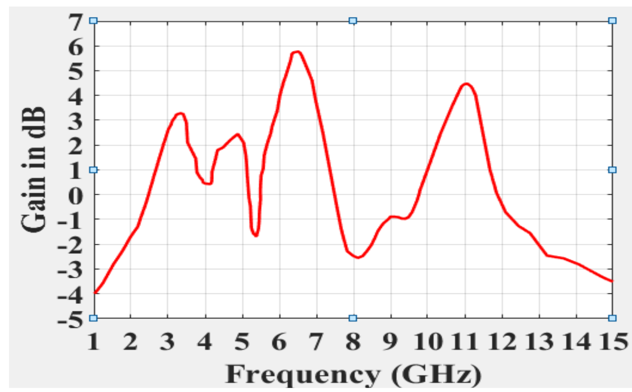


Figure 11. Measured and simulated gain vs frequency.

3.4. Surface Current and Field Analysis

The simulated surface current analysis of proposed antenna done at 6.35 GHz is shown in Fig. 12. The E field and H field distributions of proposed antenna at 6.35 GHz are shown in Fig. 13. It is observed that

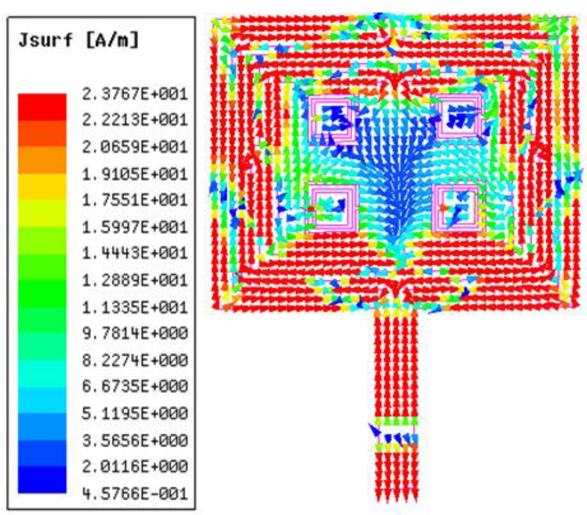
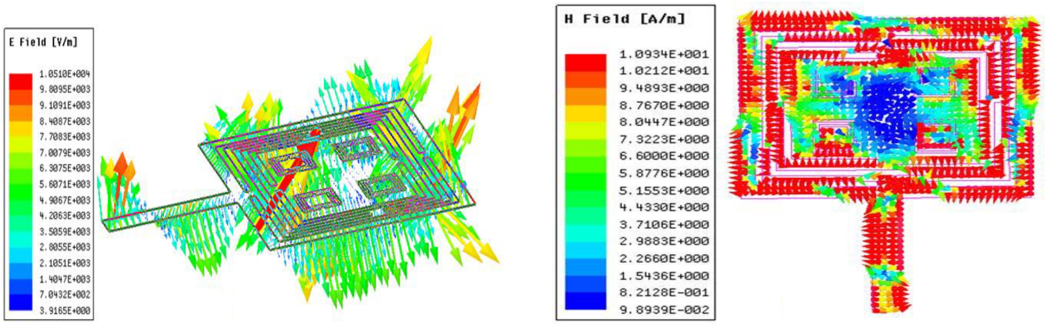


Figure 12. Simulated surface current distribution.



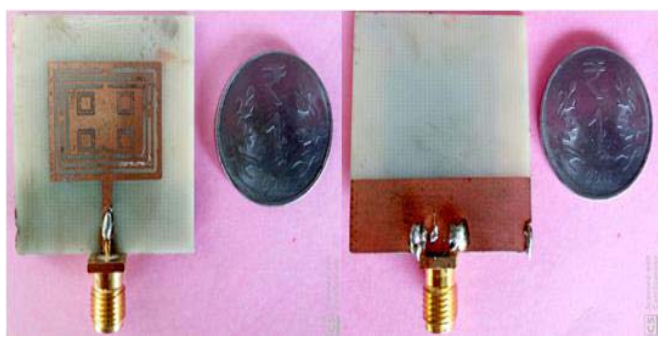
(a) (b)

Figure 13. Simulated (a) E-field and (b) H-field distribution.

the current mainly concentrates on the edges of periodic radiating patch which increases the electrical path length, and ultra-multiband frequency spectrum performance is achieved.

4. MEASURED RESULTS AND DISCUSSION

The top and bottom views of the fabricated antenna are shown in Fig. 14. The fabricated antenna is tested using Anritsu MS2037C Vector network Analyzer shown in Fig. 15. The simulated and measured return loss (S_{11}) curves for the antenna are shown in Fig. 16.



(a) (b)

Figure 14. Fabricated antenna (a) top view and (b) bottom view.

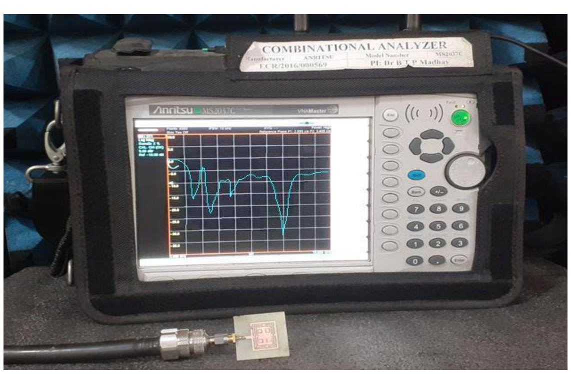


Figure 15. Return loss observed in vector network analyzer.

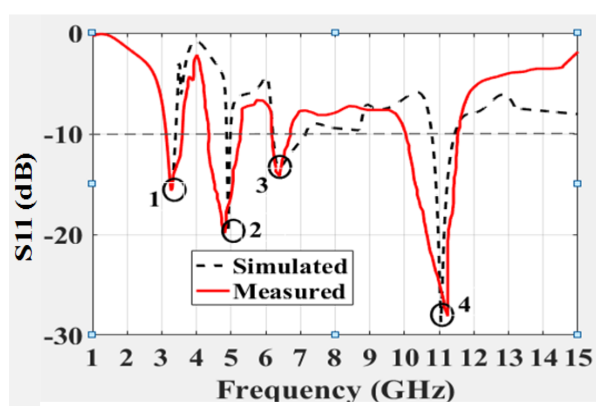


Figure 16. Simulated and measured return loss for proposed antenna.

The measured results are on par with simulated ones with small deviations. This deviation is due to limitations in measurement setup and fabrication.

The far field radiation pattern of proposed antenna is bidirectional obtained from anechoic chamber and shown in Fig. 17. The measured plots for E and H fields of the proposed antenna are taken at 3.27 GHz, 4.92 GHz, 6.35 GHz, and 11.04 GHz respectively.

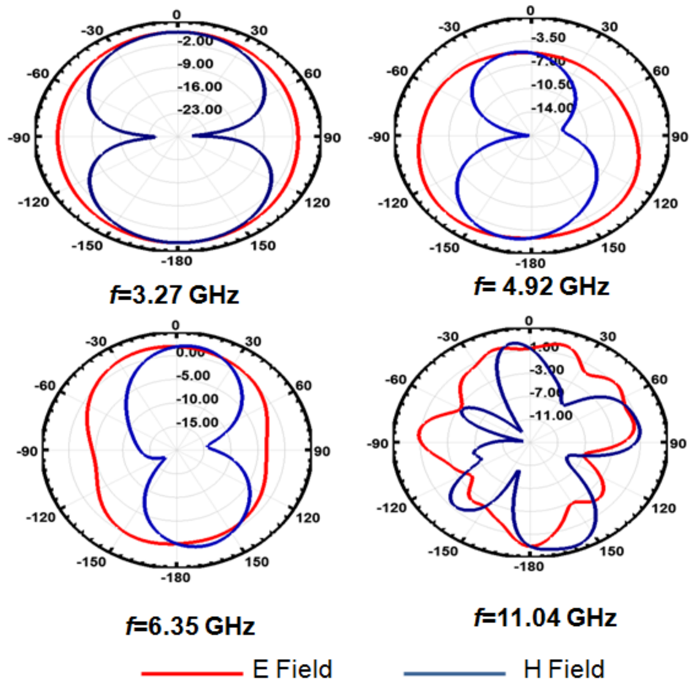


Figure 17. Simulated radiation pattern of proposed antenna at 3.27 GHz, 4.92 GHz, 6.35 GHz and 11.04 GHz.

Comparison of obtained results of the proposed antenna with the existing referred papers in the published literature is tabulated in Table 3.

Table 3. Performance comparison of proposed antenna with previously reported antennas in literature.

Ref.	Size (mm^2)	No. of Band's	Freq. of Operation (GHz)	% BW	Application
[13]	35 × 35	3	2.16/3.37/5.54	3.25, 2.06, 4.18	IMAT/WiMAX
[14]	58 × 81	3	2.4/3.5/4.4	1.2, 2.1, 2.4	WiMAX/WiFi
[15]	37 × 27	3	2.4/3.2/3.7	1.1, 1.2, 2.8	WiMAX/ Space Research
[19]	33 × 28	3	3.3/4.7/6.19	1.1/2.3/3.1	GSM/Satellite Communication
[20]	60 × 60	3	2.4/3.35/5.35	1.45/2.03/2.9	WiMAX/WLAN
[21]	36 × 49	3	2.4/3.5/5.7	5.8/3.7/1.5	WiMAX/WLAN
Proposed	**32 × 32**	4	3.27/4.92/6.35/11.04	8.34/2.0/14.68/5.41	WiMAX/WiFi/ Space/Satellite

5. CONCLUSIONS

In this paper, a patch antenna with a defected ground structure (DGS) is proposed and investigated operating at four bands. To obtain a good impedance matching and gain, the optimized dimensions of the proposed antenna are realized, and the proposed antenna is fabricated and tested. The antenna operates at 3.271 GHz (WiMax), 4.92 GHz (WiFi), 6.35 GHz (Space applications), and 11.04 GHz (Fixed Satellite applications) suitable for wireless and satellite communication applications and having impedance bandwidth impedance of 8.34% (3.10–3.37 GHz), 2.00% (4.88–4.98 GHz), 14.68% (6.21–7.194 GHz), and 5.41% (10.79–11.39 GHz) with gains 3.25, 2.45, 5.65, and 4.47 dB, respectively. The simulated and measured results of the designed antenna are consistent. In addition, a comparison is made between the designed antenna and antennas previously reported in the literature with respect to the impedance bandwidth and antenna size.

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