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Compact Reconfigurable Patch Antenna for Wireless Applications

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Abstract—A novel miniatured reconfigurable antenna for wireless applications using defective ground structure is proposed and studied. This proposed antenna generates eight different frequencies, operating at 2 GHz (IMT), 2.3 GHz (UMTS), 2.5 GHz (Wi-Fi), 2.7 GHz (Radio astronomy), 2.9 GHz (Weather radar), 4.2 GHz (Radio altimeter), 4.4 GHz (Radio determination), and 5.5 GHz (Wi-MAX) while maintaining overall compact size of $24 \times 33 \times 1.6\,\text{mm}^3$ using an FR-4 substrate having a permittivity of $\varepsilon_r = 4.4$. The proposed reconfigurable antenna consists of three switches in the slots of the patch along with rectangular defects on ground surface and a microstrip feed line. The lumped elements are used in place of three switches in the simulation to get tuneable capacitance, which is responsible for frequency reconfigurability. It makes the antenna operate at eight useful bands. The structure shows the impedance bandwidths of 6.86%, 6.04%, 2.51%, and 2.73% with gains 5 dB, 4.8 dB, 6 dB, and 6.8 dB, respectively. The designed antenna can be easily integrated on modern communication devices. A prototype of the designed antenna is fabricated, and the simulation results are compared with measured values using PIN diode switches.

1. INTRODUCTION

Nowadays, there is an ever-increasing demand for wireless communications. Antenna is the most significant part for transmitting and receiving electromagnetic waves. Antenna acts as a transducer for converting electrical signals to electromagnetic waves and is used to transmit electromagnetic waves over longer distance. Reconfigurable antennas are needed for modern communication devices. Reconfigurable antenna properties are used to obtain polarization, pattern, selectivity, and frequency of radiating structures. Reconfigurable antenna is described as an antenna that can adjust its characteristics based on the application. The available spectrum can be effectively reallocated by means of a reconfigurable antenna because of which it is widely used in multiband systems [1–5].

Reconfigurable antennas replace multiple antennas with single antennas by reducing the number and size of antennas compared to traditional antenna systems. With the widespread use of cognitive radio and wireless communication systems, frequency reconfiguration techniques are used for printed antennas with PIN diodes. Satellite and multiband wireless communication applications make use of frequency reconfigurable antennas [6]. Pattern reconfigurable antennas are used for multiple-input multiple-output (MIMO) services because of their beam reconfigurability advantages [7]. Polarized reconfigurable antennas are used to reduce fading in wireless communication systems and to reuse frequencies [8–11].

In this paper, a frequency reconfigurable antenna with an FR-4 substrate of thickness 1.6 mm is designed. The reconfigurable antenna radiates in eight different frequency bands, 2 GHz, 2.3 GHz, 2.5 GHz, 2.7 GHz, 2.9 GHz, 4.2 GHz, 4.4 GHz, and 5.5 GHz, for a variety of wireless applications. To obtain frequency reconfigurability, lumped element components (i.e., RLC; resistors, inductors, and capacitors) are used in the simulation as switches in the designed antenna radiating structure [12–19]. A 2 mm slot is reserved for the switch.

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2. PROPOSED ANTENNA DESIGN

The geometry and structural dimensions of the frequency reconfigurable antenna with and without defected ground structure (DGS) are presented in Figure 1. In the designed antenna, the radiating element is printed on an FR-4 substrate (having relative permittivity (ε_r) of 4.4, tangent loss ($\tan\delta$) of 0.019, thickness of 1.6 mm) and truncated metallic ground surface as back. The volume of the proposed reconfigurable antenna is $24 \times 33 \times 1.6\,\text{mm}^3$. Table 1 describes the dimensions of the designed antenna. Ansys High Frequency Structural Simulator (HFSS) Licensed software 2017 version is used for the simulation process. The width and length of the basic square patch antenna can be calculated by the following design equations [21, 23].

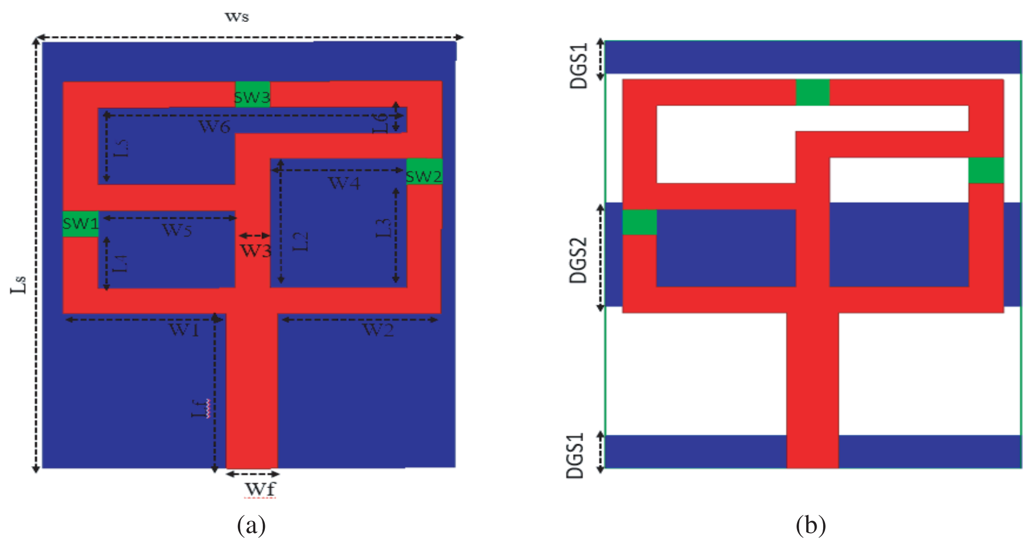


Figure 1. (a) Antenna without DGS. (b) Antenna with DGS.

Calculation of the Patch Width:

$$width = \frac{c}{2f_0\sqrt{\frac{\varepsilon_r+1}{2}}} \tag{1}$$

Effective Refractive Index:

$$(\varepsilon_{\mathit{eff}}) = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+12\left(\frac{h}{w}\right)}}\right] \tag{2}$$

Calculation of the Patch Length:

$$length = \frac{c}{2f_0\sqrt{\varepsilon_{\mathit{eff}}}} - 0.824h\left(\frac{\varepsilon_r\left(\varepsilon_{\mathit{eff}}+0.3\right)\left(\frac{w}{h}+0.264\right)}{\left(\varepsilon_{\mathit{eff}}-0.258\right)\left(\frac{w}{h}+0.8\right)}\right) \tag{3}$$

The guided wavelength and quality parameters of the designed antenna are optimised for improved radiation efficiency [26].

Antennas can achieve low values of reflection coefficients in the desired frequency band ($S_{11} < -10\,\text{dB}$) with perfect matching. The gain (G) and directivity (D) of the proposed antenna correlate with radiation efficiency. Gain (G) is usually expressed in decibels (dB) and is given as

$$G\,(\text{dB}) = 10 \times \log_{10}(\eta_{rad} D)$$

Table 1. Dimensions of proposed antenna.

Parameter	**Notation**	**Dimension (mm)**
Length of substrate	L_s	33
Width of substrate	W_s	24
Length of strip	L_f	12
Width of strip	W_f	3
Length of slit	L_2	10
Length of slit	L_3	8
Length of slit	L_4	4
Length of slit	L_5	6
Length of slit	L_6	2
Width of slit	W_1	9.5
Width of slit	W_2	9.5
Width of slit	W_3	2
Width of slit	W_4	8
Width of slit	W_5	8
Width of slit	W_6	18
Switch size	SW_1	$2 \times 2\,\text{mm}^2$
Switch size	SW_2	$2 \times 2\,\text{mm}^2$
Switch size	SW_3	$2 \times 2\,\text{mm}^2$
DGS length	DGS_1	2.5
DGS length	DGS_2	8

3. RESULTS AND DISCUSSIONS

3.1. Parametric Analysis

The proposed antenna with improved bandwidth and gain has been discussed in parametric analysis. The variability of the dimensions in the DGS, various DGS shapes, the W_f feed strips, and the incorporation of different substrates helps in analysing the proposed antenna for different parametric qualities when all three switches are at ON state. Under the condition of all the three switches (SW_1, SW_2, and SW_3) in ON state, the frequency bands, impedance band width percentages, and gains for different parametric qualities are noted in Table 3.

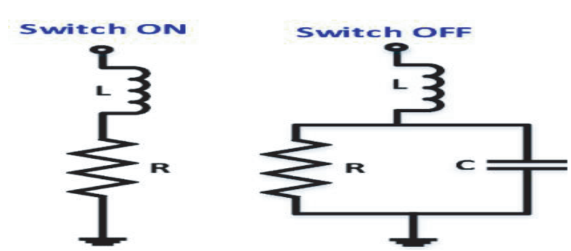


Figure 2. Equivalent circuit models of the ON and OFF states of the switch.

3.1.1. Return Loss Variation with Different Switching Conditions

From the above Figure 1, three slots, each with 2 mm, are allocated for the switches. PIN diodes act as a variable resistor in the radio frequency (RF), and they have the minor problem of complex circuitry for ON and OFF states. PIN diodes have an inductance (L_b) in the equivalent circuit for both ON and OFF states. Low resistor (R_{bS}) will exist in the ON state (forward biased), and during OFF state (reversed biased), the resistor (R_{bP}) is parallel with capacitaor (C_c) as depicted in Figure 2. By making the switch ON and OFF, there are eight conditions. From these conditions we get eight different frequency bands as shown in Figure 3 listed in Table 2.

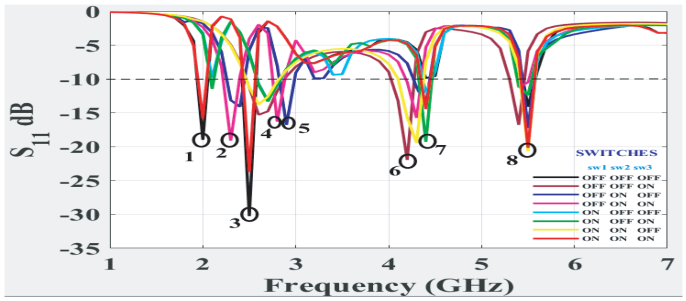


Figure 3. Simulated return loss curve for different frequency bands for all conditions.

Table 2. Tuning states of reconfigurable antenna.

S. NO	**SW1**	**SW2**	**SW3**	**Frequency bands (GHz)**
1	OFF	OFF	OFF	2, 2.5, 5.5
2	OFF	OFF	ON	2.6, 4.2, 5.4
3	OFF	ON	OFF	2.4, 2.9, 4.4, 5.5
4	OFF	ON	ON	2.3, 2.8, 4.3, 5.4
5	ON	OFF	OFF	2.7, 4.4, 5.5
6	ON	OFF	ON	2.1, 2.7, 4.4, 5.5
7	ON	ON	OFF	2.6, 4.3, 5.5
8	ON	ON	ON	2, 2.5, 4.4, 5.5

Table 3. Parametric performance analysis.

Parameter Variation		Frequency bands (GHz)	Impedance Bandwidth (%)	Gain in dB
Width of Strip feed W_f (mm)	2	4.2, 5.4	2.2, 4.4	4.1, 6.4
	3	**2, 2.5, 4.4, 5.5**	**6.86, 6.04, 2.51, 2.73**	**5, 4.8, 6, 6.8**
	4	2.6, 4.3, 5.4	5.4, 2.1, 2.6	4.6, 5.6, 6.4
Glass	$\varepsilon_r = 5.5$	2.6, 4	5.4, 1.9	4.6, 5.1
RT Duroid	$\varepsilon_r = 2.2$	2.7, 4.7	5.8, 2.9	3.9, 4.4
FR 4	$\boldsymbol{\varepsilon_r = 4.4}$	**2, 2.5, 4.4, 5.5**	**6.86, 6.04, 2.51, 2.73**	**5, 4.8, 6, 6.8**
Without DGS		4.2, 4.8	2.4, 3.1	4.1, 5.9
With DGS (Proposed)		**2, 2.5, 4.4, 5.5**	**6.86, 6.04, 2.51, 2.73**	**5, 4.8, 6, 6.8**

3.1.2. Return Loss Curves with and without DGS

The designed structures with and without DGS are shown in Figure 4. Due to the introduction of the DGS into the proposed antenna, we get a greater number of frequency bands. The simulated return loss curves when all three switches are at ON condition are depicted in Figure 5.

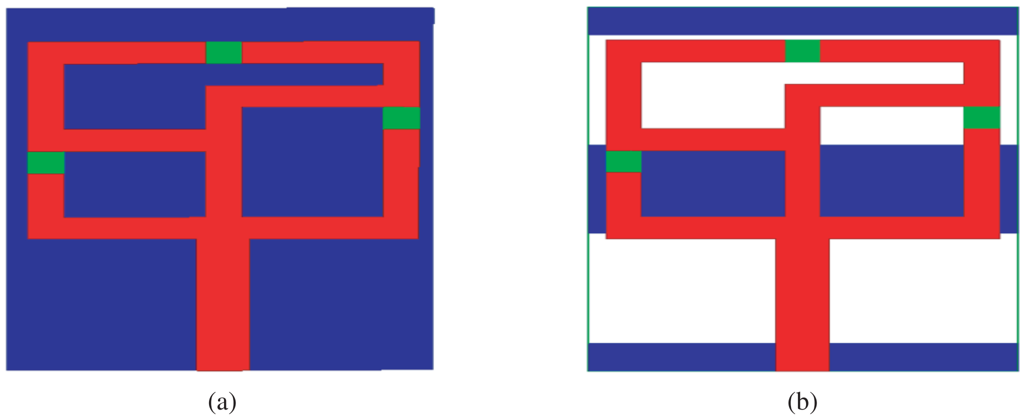


Figure 4. Proposed antenna. (a) Antenna without DGS. (b) Antenna with DGS.

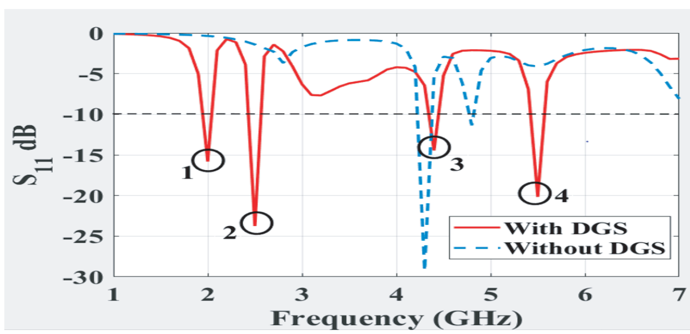


Figure 5. Simulated return loss of designed antenna without and with DGS.

3.1.3. Return Loss Curves for Various Substrates

As shown in Figure 6, the parametric variations of proposed antenna with various substrates namely FR4 ($\varepsilon_r = 4.4$), RT Duroid ($\varepsilon_r = 2.2$), and Glass ($\varepsilon_r = 5.5$) are simulated when all switches at ON state. The performance of the FR4 substrate is found to be better with relevance to RT Duroid and Glass.

3.1.4. Variability in Return Loss for Various DGS

By changing different DGSs the parametric analysis was performed, as depicted in Figure 7. The simulated return loss curves when all switches are at ON state for various DGS is visualized in Figure 8.

3.1.5. Variability in Return Loss for Various Strip Feed Widths W_f

When all the switches (SW_1, SW_2, and SW_3) are at ON state the return loss curves under different widths (2 mm, 3 mm, and 4 mm) are depicted in Figure 9.

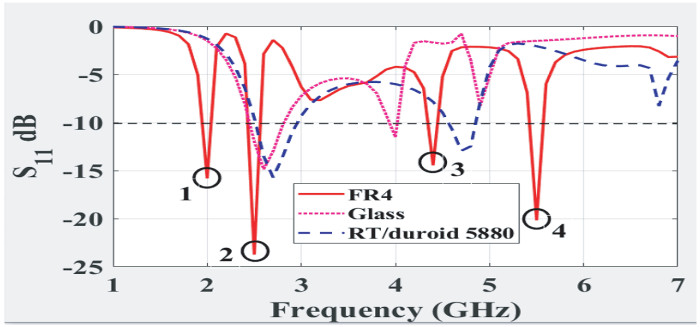


Figure 6. Simulated return loss curves for various substrates.

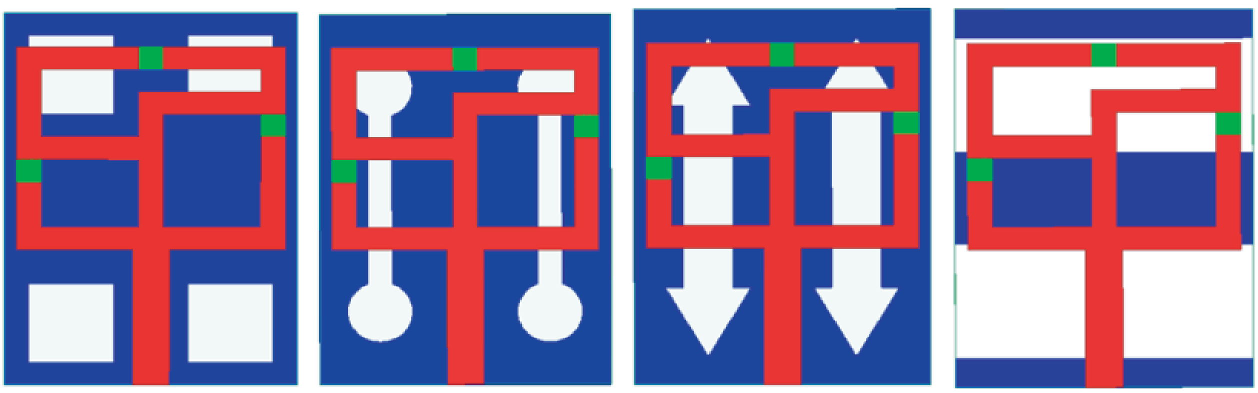


Figure 7. Different DGS structures. (a) Square DGS. (b) Circular dumbbell DGS. (c) Triangular dumbbell DGS. (d) Proposed DGS.

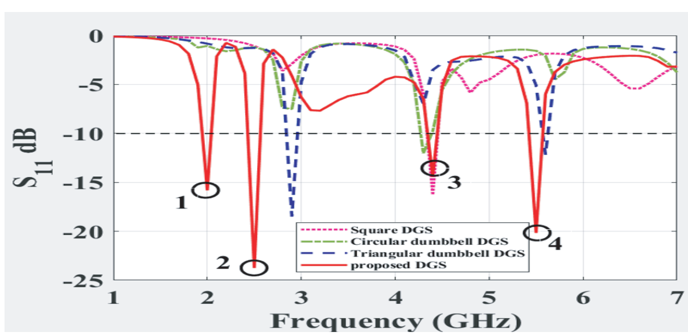


Figure 8. Simulated return loss curves for different DGS.

3.2. Voltage Standing Wave Ratio (VSWR)

The designed antenna exhibits VSWR less than 1.5 for all the frequency bands, indicating the optimal matching of the antenna. When we chose the best condition among all eight conditions, i.e., when all switches (SW_1, SW_2, and SW_3) are in the ON state, the designed antenna exhibits VSWR less than 1.5 for all the frequency bands, indicating the optimal matching of the antenna when all switches (SW1, SW2 and SW3) are in ON state, as illustrated in Figure 10.

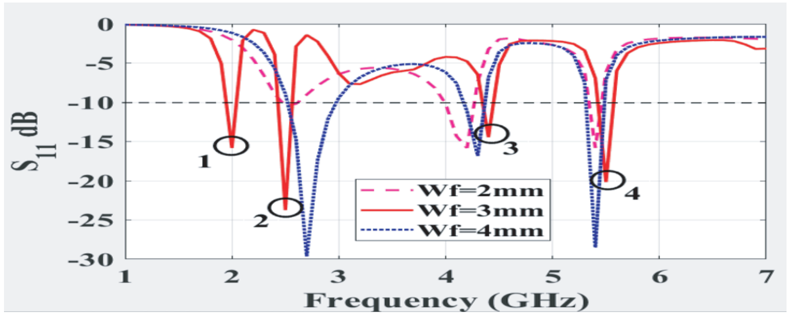


Figure 9. Simulated return loss curves for different strip widths (w_f).

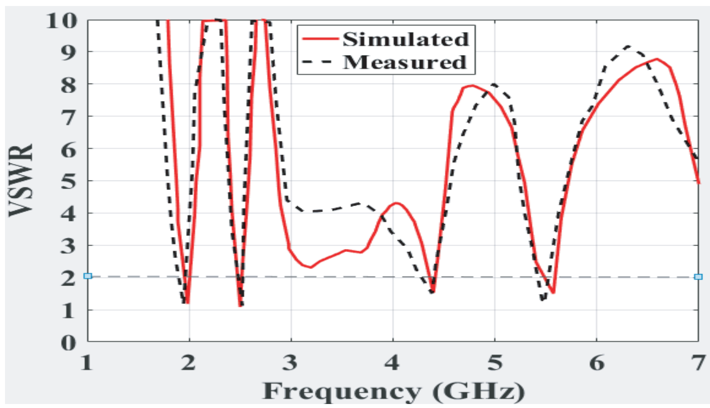


Figure 10. VSWR of the proposed antenna when all switches are at ON state.

3.3. Gain

The measured and simulated gains in dB are shown in Figure 11 for the proposed antenna design. It is observed that simulated and measured gain results are in good agreement.

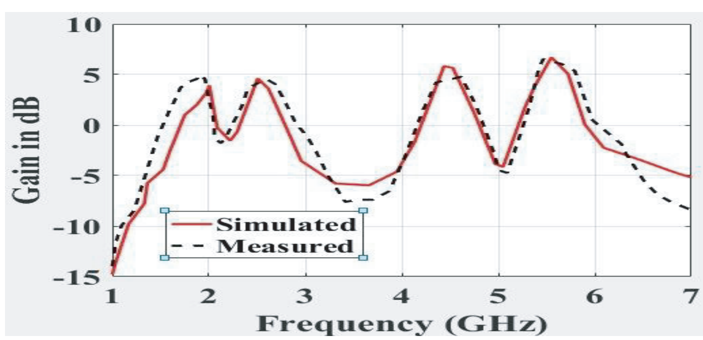


Figure 11. Frequency vs gain of the proposed antenna when all switches are at ON state.

3.4. Radiation Efficiency

The ratio of the total power radiated by an antenna to the net power accepted by the antenna from the connected transmitter known as radiation efficiency is depicted in Figure 12.

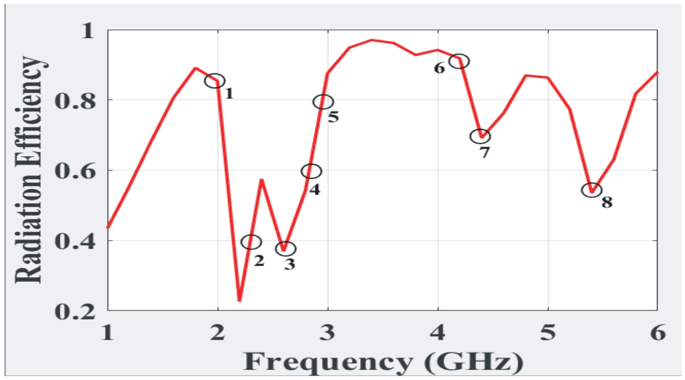
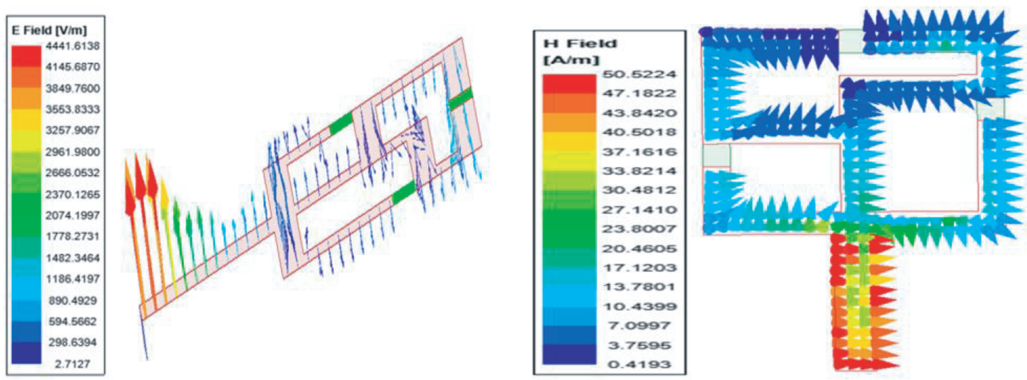


Figure 12. Frequency vs radiation efficiency of proposed antenna at all eight frequencies.



(a) (b)

Figure 13. Simulated (a) E-field, (b) H-field distribution of proposed antenna.

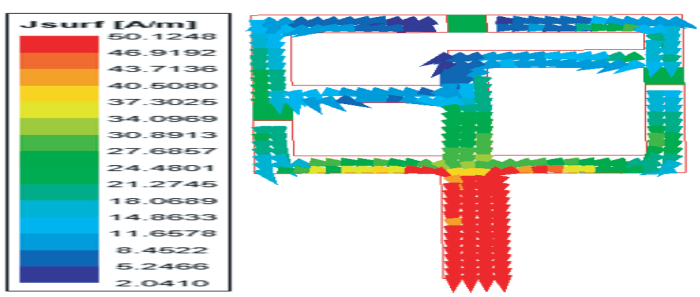


Figure 14. Simulated surface current distribution of the designed antenna.

3.5. Field Analysis and Surface Current

The electric E-field and magnetic H field distributions of the proposed antenna are depicted in Figure 13. For the proposed design under the switches (SW_1, SW_2 and SW_3) in ON condition, the simulated surface current analysis is depicted in Figure 14. From the figure it can be observed that focuse of the flow is majorly on the edges of occasional transmitting patch.

The proposed antenna's electric field distributions at eight different frequencies are visualized in Figure 15, which provides electromagnetic waves interaction with the antenna structure.

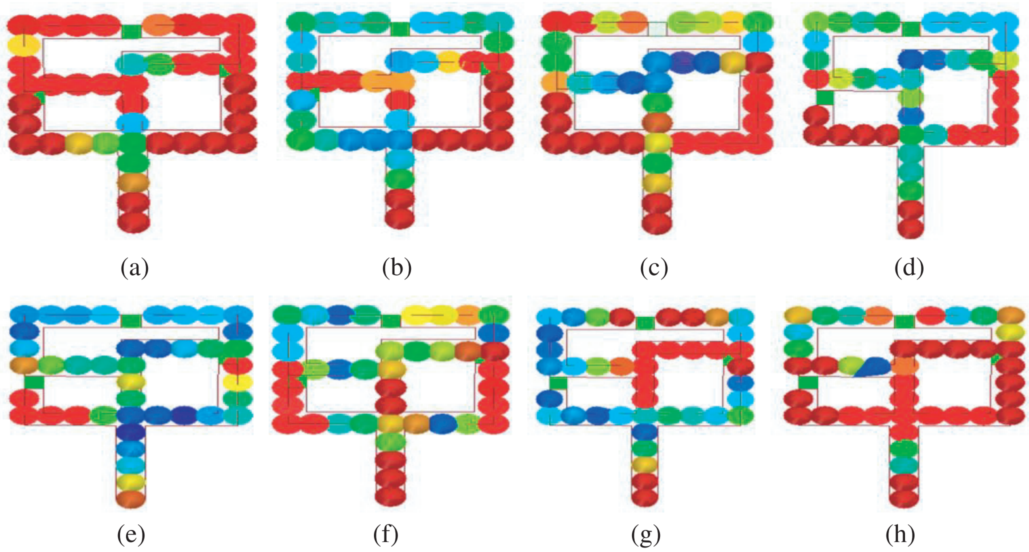


Figure 15. The electric-field distribution of the designed antenna at: (a) 2 GHz, (b) 2.3 GHz, (c) 2.5 GHz, (d) 2.7 GHz, (e) 2.9 GHz, (f) 4.2 GHz, (g) 4.4 GHz, (h) 5.5 GHz.

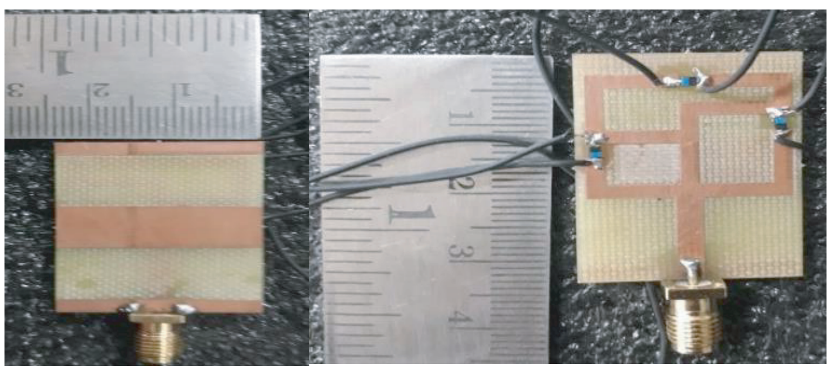


Figure 16. Fabricated antenna top view and bottom view.

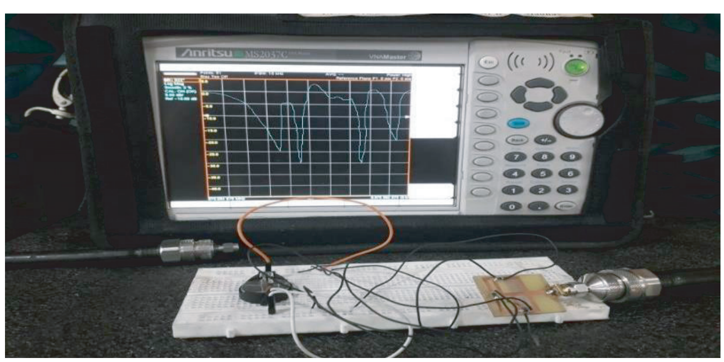


Figure 17. Return loss observed in VNA when all switches are at ON condition.

4. MEASURED RESULTS AND DISCUSSIONS

The fabricated model of the proposed antenna is represented in Figure 16. The antenna is fabricated using an FR-4 substrate of thickness 1.6 mm & relative permittivity $\varepsilon_r = 4.4$. The antenna is fed

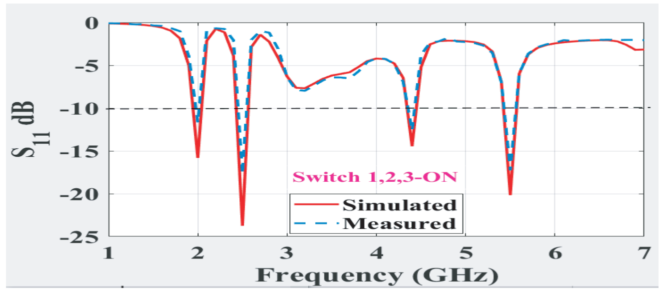


Figure 18. Measured and simulated return loss of proposed design.

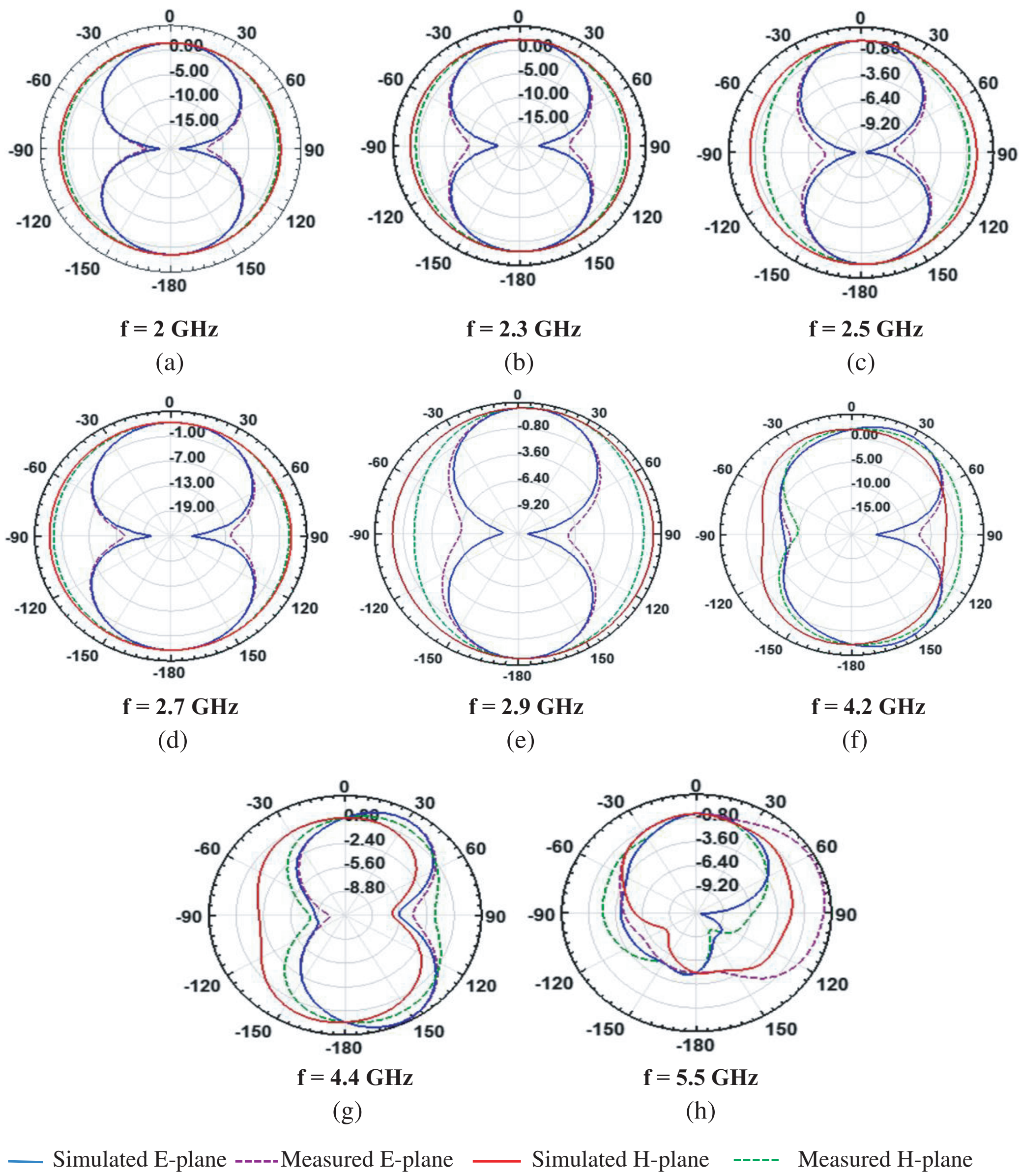


Figure 19. The simulated and measured radiation patterns of antenna in E-plane (XOY) and H-plane (XOZ) at: (a) 2 GHz, (b) 2.3 GHz, (c) 2.5 GHz, (d) 2.7 GHz, (e) 2.9 GHz, (f) 4.2 GHz, (g) 4.4 GHz, (h) 5.5 GHz.

through an SMA port for the practical operations. Three lumped element (RLC) switches, as presented in Table 2, have been incorporated to obtain the various modes of operation. The rationale behind selecting the lumped element switch is that it can be easily modelled in Computer Simulation Technology (CST) Microwave Studio (MWS) as a resistor of 0.1 μΩ and 1000 GΩ, to represent the switch-ON and switch-OFF states, respectively.

An Agilent N5242A PNA-X series Vector Network Analyzer (VNA) as shown in Figure 17 is used for measuring the reflection coefficient (S_{11}) of the reconfigurable antenna.

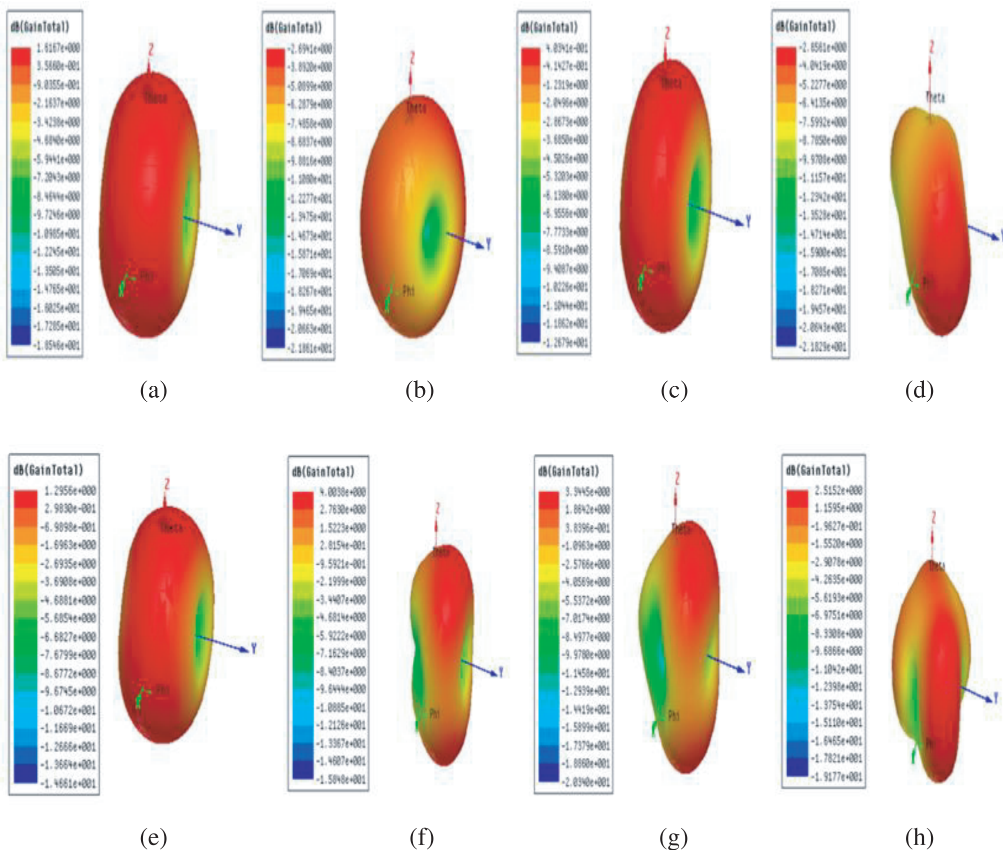


Figure 20. The 3D far-field gain pattern at: (a) 2 GHz, (b) 2.3 GHz, (c) 2.5 GHz, (d) 2.7 GHz, (e) 2.9 GHz, (f) 4.2 GHz, (g) 4.4 GHz, (h) 5.5 GHz.

Table 4. Comparison of the recommended antenna with existing works.

Ref.	No. of operating bands	Dimensions (mm^2)	Frequency (GHz)	BW (MHz)	Gain (dB)
[20]	3	58×48	2.3, 2.4, 2.5	112–159	1.92–3.2
[22]	3	40×40	2.45, 3.5, 5.2	147–182	1.7–3.4
[24]	3	35×40	2.45, 3.5, 5.2	135–250	1.48–3.26
[25]	6	35×40	3.90, 4.2, 4.42, 4.82	220–320	1.92–3.88
[27]	3	39×37	2.45, 3, 5.2	211–880	1.32–2.32
Proposed design	**8**	**24×33**	**2, 2.3, 2.5, 2.7, 2.9, 4.2, 4.4, 5.5**	**251–959**	**4.8–6.8**

Measured and simulated reflection coefficients are shown in Figure 18 of the frequency reconfigurable antenna, and it is observed that the measured and simulated results are in good agreement.

Radiation plots can be obtained by keeping the prototype in an anechoic chamber. The E and H field radiation patterns of the proposed antenna are obtained from the anechoic chamber in two directions and depicted in Figure 19. Measured E and H fields of the proposed antenna are taken at eight different frequencies.

The 3D far field gain patterns at eight different frequencies with all the switching states of the reconfigurable antenna are shown in Figure 20.

The comparison of the proposed frequency reconfigurable antenna with the aforementioned literature is simulated in Table 4, which indicates that the designed antenna has higher gain, compact size, with the maximum number of operating frequencies, and yields maximum band widths as compared to [14, 16, 17, 21, 24].

5. CONCLUSION

The current work has focussed on designing and experimentally validating a frequency reconfigurable antenna. The antenna was reconfigured to operate in eight different frequency band modes. The desired gain and impedance matching were obtained by optimising the dimensions of the proposed antenna which was fabricated, realized, and tested. To achieve the desired operating characteristics, different switching states were required. This proposed antenna generates eight different frequencies which operate at 2 GHz (IMT), 2.3 GHz (UMTS), 2.5 GHz (Wi-Fi), 2.7 GHz (Radio astronomy), 2.9 GHz (Weather radar), 4.2 GHz (Radio altimeter), 4.4 GHz (Radio determination), and 5.5 GHz (Wi-MAX). The proposed antenna has the -10 dB impedance bandwidth values 6.86%, 6.04%, 2.51%, and 2.73% with gains 5 dB, 4.8 dB, 6 dB, and 6.8 dB, respectively. The proposed reconfigurable antenna has many advantages such as compact size, easy fabrication, light weight, simple integration, and low cost. The designed reconfigurable antenna was intended for the use in military purposes, satellite communications, and modern communication devices (i.e., laptops and tablets). PIN diodes are used in the fabricated prototype, and measurements were carried out for the radiation patterns and reflection coefficient. There is a good agreement between simulated and measured results

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