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DESIGN AND ANALYSIS OF FREQUENCY RECONFIGURABLE MICROSTRIP ANTENNA WITH FRACTAL GROUND PLANE FOR MULTIBAND WIRELESS APPLICATIONS

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Abstract: The reconfigurable microstrip patch antenna in the current work has a new design and can operate at numerous frequencies, specifically at 8.17 GHz, 11.13 GHz, 15.77 GHz, and 17.46 GHz in the OFF state and 8.38 GHz, 11.13 GHz, 14.51 GHz, 16.20 GHz, 17.46 GHz, and 18.52 GHz in the ON state. The switching element used for antenna reconfiguration is a single PIN diode modeled on High Frequency Structure Simulator (HFSS) software. The ON/OFF switching configurations of the diode make the antenna capable of resonating at different frequencies in the X-band (8-12 GHz) and Ku-band (12-18 GHz) applications. Inclusion of square fractal slots on the ground plane leads to considerable improvement in bandwidth and gain. The proposed antenna is designed on a low-cost FR-4 substrate with a dielectric constant of 4.4 and a thickness of 1.6 mm. The proposed antenna shows good performance in terms of return loss, radiation pattern, and gain.

Keywords- Reconfigurable, fractal, return loss, PIN diode, VSWR, radiation efficiency

1. Introduction

From a very long time ago, microstrip patch antennas have been a crucial component of wireless communication. Many design strategies have been used throughout the years, which have boosted their use for modern wireless applications [1]. The main design objectives for enhanced applications of microstrip patch antennas have been high gain and broad bandwidth. The most recent ones include fractal geometries and reconfigurability [2-3]. Other strategies, such as flawed ground and slotted patches, have also been developed or used by researchers. Fractals are geometries that have unique properties such as self-similarity and space-filling [4-5]. They are made up of scaled versions of themselves and have been vastly implemented on microstrip patch antennas to obtain wideband/multiband characteristics and miniaturization. In [6], a considerable improvement in bandwidth of about 3.5 times the initial has been attained by introduction of a fractal-shaped slot on the ground plane. Combination of different fractal shapes can lead to reduction in the size of microstrip antennas by lowering the resonant frequency, leading to effective miniaturization of the antenna [7-9]. Commercial communication systems require antennas that are miniature, easy-to-fabricate and multifunctional to cope with the huge advancements in wireless communication technologies and the purpose can be achieved by merging antenna reconfiguration with fractal shapes [10-11]. An interesting methodology and design for fractal and reconfigurable antennas has been proposed in [12]. Antennas with frequency reconfigurability can cover multiple bands and hence, can be exploited for multiple applications [13-14]. This paper presents and discusses a frequency reconfigurable microstrip patch antenna having a fractal ground plane for bandwidth enhancement. Reconfigurable microstrip patch antennas have become a subject of increasing interest in recent years due to their potential to adapt to different operating conditions and improve the overall performance of wireless communication systems [15-17].

These antennas are fabricated using modifications in the physical design by disconnecting and connecting different parts of the radiating element through a switching device that gives a modification in the distribution of current within the radiator [18-19]. There are various types of on and off switches that are applied to get redistribution of current in the radiator circuit [20-21].

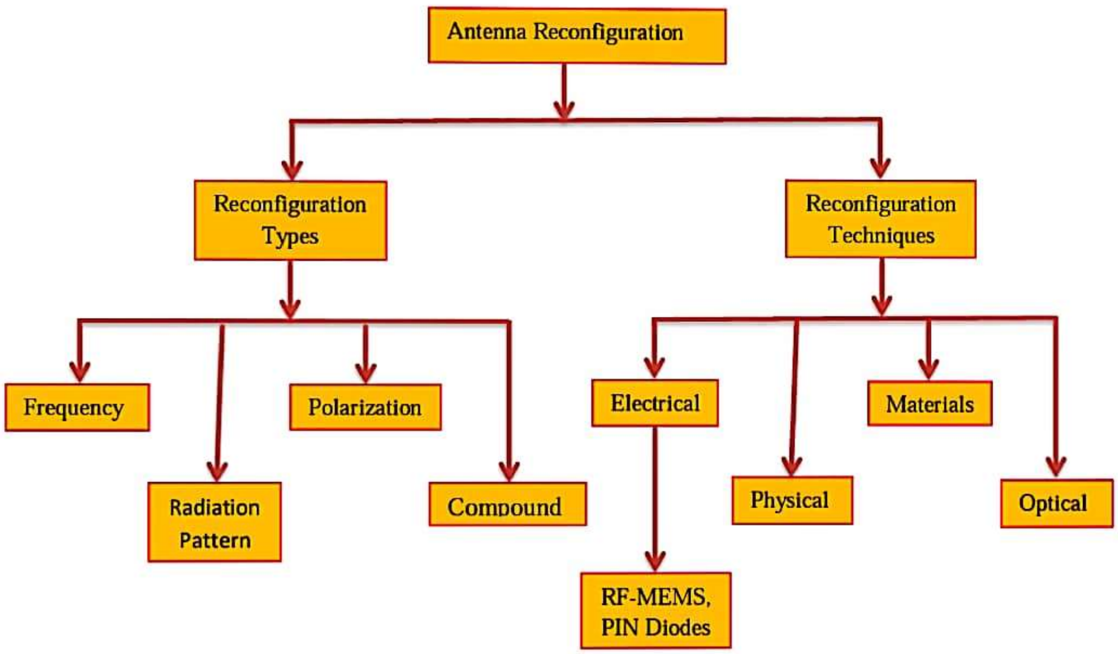


Fig. 1: Varieties and methods of antenna reconfiguration

The switching can be done using a PIN diode, RF MEMS or Varactor diode, lumped elements, or capacitance switches. Varactor and PIN diode can perform faster and can be a replacement for the RFMEMS [22-23]. The switching speed of the PIN diode is 1-100 ns. It has a more dynamic ability to get a reconfigurable antenna [24-25]. The reference articles present many reconfigurable antennas for different wireless applications. Frequency and pattern reconfigurability with the help of PIN diode and Vector diode is presented in the reconfigurable antenna [26-27].

2. Proposed Antenna: Evolution and Geometry

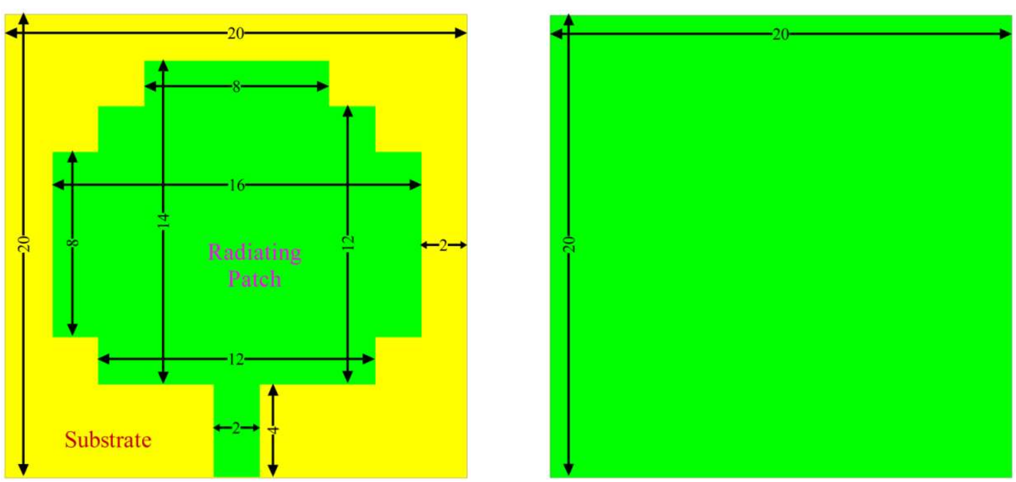
The proposed design obtains through the multiple stages of optimization as shown in fig.2 and 3. At the beginning, a rectangular shaped FR4 substrate is used as the base of the antenna. The rectangular shaped patch can be designed as follows:

$$W = \frac{c}{2f}\sqrt{\frac{2}{\varepsilon_r+1}} \quad , \; L = L_{ef} - 2\Delta l$$

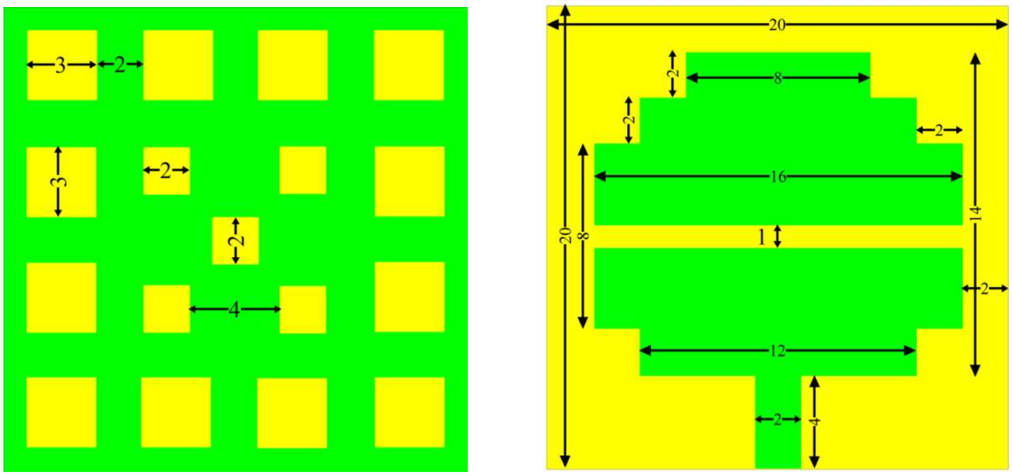
$$L_{ef} = \frac{c}{2f\sqrt{\varepsilon_{re}}} \quad , \; \varepsilon_{re} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1 + \frac{12h}{W}\right]^{-1/2}$$

$$\Delta l = 0.412h\frac{(\varepsilon_{re} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{re} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

Initially, a proposed microstrip patch antenna, as shown in Fig. 2, was designed on low-cost FR4-epoxy substrate material with thickness 1.6 mm and relative permittivity of 4.4. The radiating patch is excited by providing a thin microstrip-line feed [18]; the feed-line length and width are kept to 4 mm and 2 mm respectively. The dimensional structure of the proposed antenna is 20 × 20 mm^2 and the plain ground plane, as shown in Fig. 2(b), of the designed simple microstrip patch antenna is made defective by using square-shaped fractal slots, as shown in Fig. 2(c). The initial square-slots etched on the ground have a dimension of 3 × 3 mm^2. Scaling them down by a factor of two, 2 × 2 mm^2 square slots are next etched on the ground plane. Scaling them down by one again, a single 2 × 2 mm^2 square slot is made in the center, making the ground plane defect. The Fig. 2(d) represent the PIN diode OFF state condition with 8 mm × 1 mm slot etched on the middleware portion on radiating patch, which have fulfill the reconfigurable criteria for multiband wireless applications.



(a) (b)



(c) (d)

Fig. 2: Schematic of (a) Simple Microstrip Patch Antenna, (b) Plain Ground Plane, (c) Fractal Ground Plane, and (d) Diode OFF state condition of radiating patch [Dimensional unit: mm]

The final geometry of the proposed antenna is developed on the initially designed plain ground with fractal ground plane. The switching element utilized for antenna reconfiguration is a single PIN diode that is placed in the center of a rectangular slot made on the antenna patch, as shown in Fig. 3. The dimensions of the PIN diode modeled on HFSS have been taken as 1 mm × 1 mm from the technical datasheet of Skyworks SMP1340 series, surface mountable PIN diodes [21]. The equivalent RLC circuit of the diode has OFF and ON states as shown in Fig. 4 (a) and 4(b) respectively.

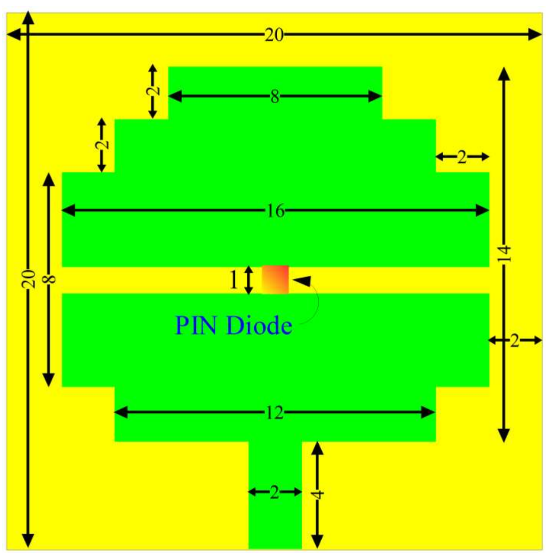


Fig. 3: Schematic of the proposed antenna design (Diode ON state condition) [Dimensional unit: mm]

The PIN diode incorporated is assumed to behave as a short circuit, series combination of inductance (L_s) and resistance (R_s), in the conducting/ON state and as an open circuit, parallel combination of resistance (R_p) and capacitance (C_p) with the inductance (L_s) in series, in the non-conducting/OFF state. The model value used for the series inductance in both the ON and OFF states of the diode is L_s = 0.7 nH, while the model value for series resistance in the ON state is R_s = 1.2 Ω. For the OFF state, the model values used for the parallel combination of capacitance and resistance are C_p = 0.3 pF and R_p = 5 MΩ respectively [8-15].

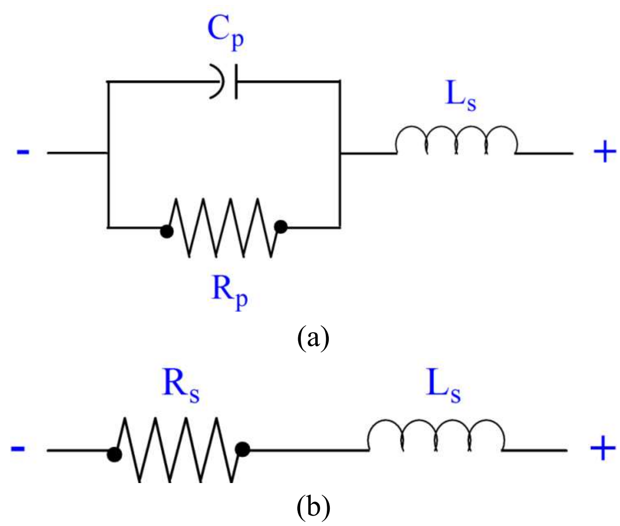


Fig. 4: (a) ON-State and (b) OFF-State RLC equivalent circuit of the proposed antenna [L_s = 0.7 nH, R_s = 1.2 Ω, C_p = 0.3 pF, and R_p = 5 MΩ]

3. Results and Discussion

The proposed antenna design and simulated using HFSS simulation tool. HFSS uses the finite element method (FEM) to break down the computational domain into smaller parts and solve the problem. Results of the simulation are examined in this section. Simulation results show that a discrete sweep is more accurate than using a continuous sweep at each frequency point. This saves time and memory, and the antenna's performance parameters and radiation characteristics are discussed.

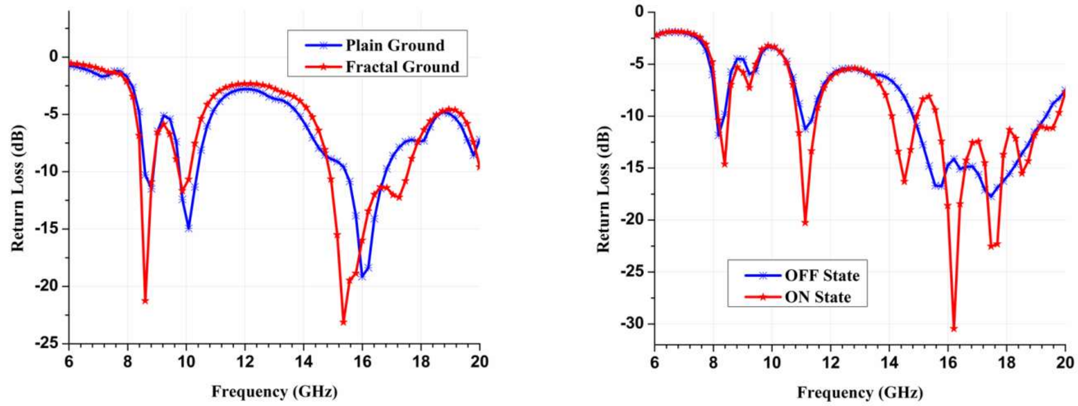
The Fig. 5(a) and table 1 represents the data of plain ground geometry and fractal ground geometry of the antenna. The plain ground antenna has operating bands (8.38-9.02) GHz with resonated on 8.81 GHz, (9.65-10.50) GHz with resonated on 10.07 GHz, and (15.35-16.83) GHz with resonated on 15.98 GHz, the plain ground antenna has peak gain 2.36 dBi, 7.75 dBi, and 6.08 dBi at respectively resonated bands (c.f. Fig. 6(a) & table 1). The fractal ground plane geometry represents the operating band (8.38-9.02) GHz with resonated at 8.60 GHz, (9.65-10.28) GHz with resonating at 9.86 GHz, and (14.72-17.67) GHz with resonated on 15.35 GHz, the fractal ground plane antenna has peak gain 5.61 dBi, 2.28 dBi, and 13.87 dBi at respectively resonated bands (c.f. Fig. 6(a) & table 1). Compared with the plain and fractal geometry of the microstrip patch antenna, the fractal ground has obtained the enhanced gain and bandwidth.

Table 1: Performance characteristics of the design configuration

Design Configuration	Operating Band (GHz)	Resonant Frequency (GHz)	Return Loss (dB)	Peak Gain (dBi)	Radiation Efficiency (%)	VSWR
Plain Ground	8.38-9.02	8.81	-11.49	2.36	72.50	1.07
	9.65-10.50	10.07	-14.93	7.75	65.40	1.52
	15.35-16.83	15.98	-19.14	6.08	57.07	1.62
Fractal Ground	8.38-9.02	8.60	-21.24	5.61	71.80	1.62
	9.65-10.28	9.86	-11.66	2.28	66.50	1.92
	14.72-17.67	15.35	-23.12	13.87	61.80	1.23
Diode OFF-State	7.96-8.38	8.17	-11.85	9.12	71.13	1.44
	10.92-11.55	11.13	-11.22	5.62	85.43	1.20
	14.72-19.36	15.77	-16.72	8.75	75.63	1.58
		17.46	-17.71	7.61	77.90	1.93
Diode ON-State	7.96-8.60	8.38	-14.62	13.30	80.96	1.52
	10.71-11.55	11.13	-20.25	4.67	85.43	1.47
	14.08-15.14	14.51	-16.29	13.17	73.36	1.05
	15.56-19.78	16.20	-30.44	9.92	88.16	1.75
		17.46	-22.52	7.91	86.78	1.15
		18.52	-15.50	14.55	79.03	1.95

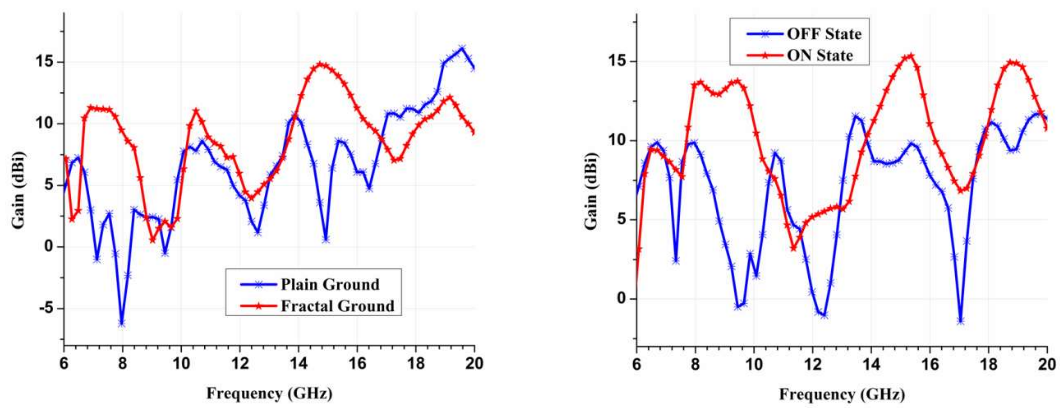
The Fig. 5(b) and table 1 represents the data of the proposed antenna, it is found that in the ON/OFF state conditions, the OFF state has obtained operating bands (7.96-8.38) GHz with resonated on 8.17 GHz, (10.92-11.55) GHz with resonated on 11.13 GHz, and (14.72-19.36) GHz with resonated on 15.77 GHz & 17.46 GHz, the OFF state antenna has obtained peak gain 9.12 dBi, 5.62 dBi, 8.75 dBi, and 7.61 dBi at respectively resonated bands (c.f. Fig. 6(b) & table 1). The ON state conditions has obtained operating bands (7.96-8.60) GHz with resonated on 8.38 GHz, (10.71-11.55) GHz with resonated on 11.13 GHz, (14.08-15.14) GHz with resonated on 14.51 GHz, and (15.56-19.78) GHz with resonated on 16.20 GHz, 17.46 GHz, & 18.52 GHz, the ON state antenna has obtained peak gain 13.30 dBi, 4.67 dBi, 13.17 GHz, 9.92 dBi, 7.91 dBi, & 14.55 dBi at respectively resonated bands (c.f. Fig. 6(b) & table 1).

It is observed that the S_{11} parameter value is well below -10 dB for both the ON and OFF switching conditions of the PIN diode. Fig. 7(a) represents the radiation efficiency plot of plain and fractal ground geometry, and Fig. 7(b) represents the radiation efficiency plot of the ON and OFF state PIN diode condition of the proposed reconfigurable antenna. The whole antenna design consideration has performed the satisfactory existence values of the radiation efficiency.



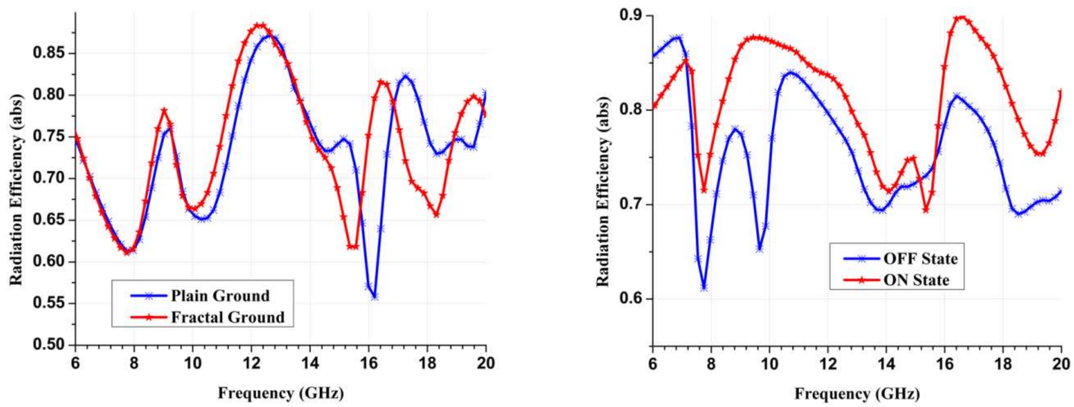
(a) (b)

Fig. 5: Plot of S_{11} parameters versus frequency of entire design configuration



(a) (b)

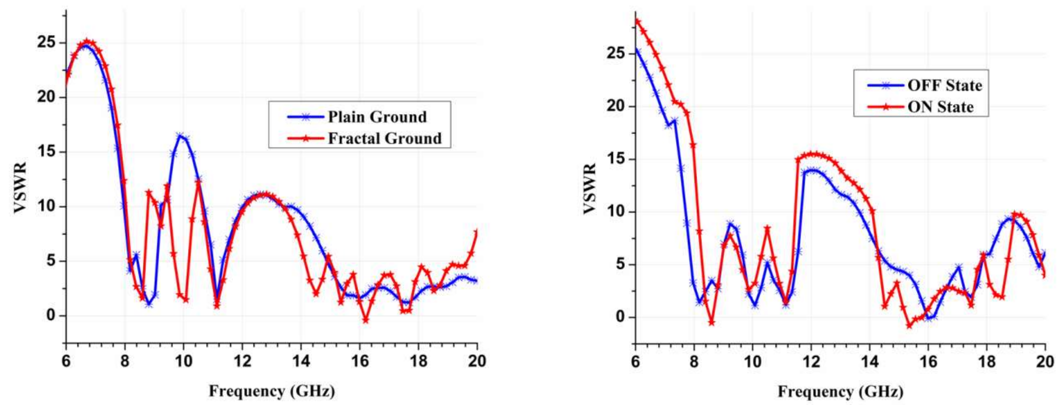
Fig. 6: Plot of gain parameters versus frequency of entire design configuration



(a) (b)

Fig. 7: Plot of radiation efficiency parameters versus frequency of entire design configuration

The plot of VSWR versus frequency for plain/fractal ground and the ON/OFF switching conditions of the PIN diode is as shown in Fig. 8(a) and 8(b) respectively, and it are observed that the VSWR value is well below 2 at all resonant frequencies. The plot of antenna peak gain in dBi is as shown in Fig. 5.

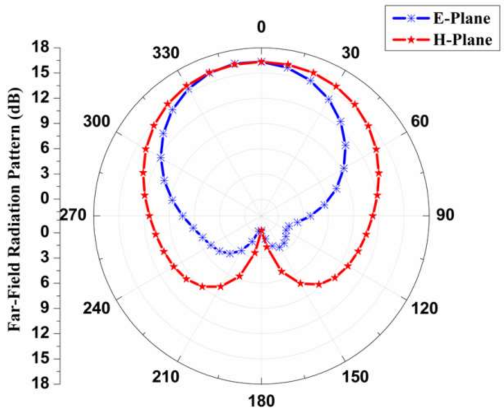


(a) (b)

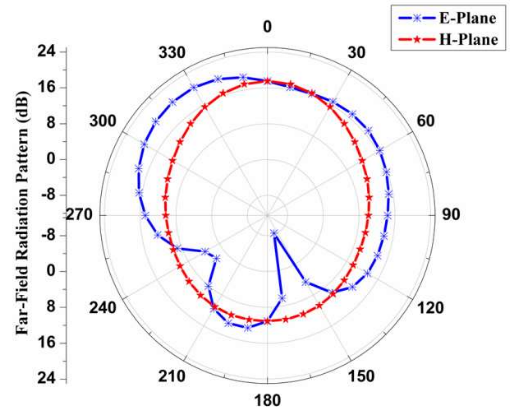
Fig. 8: Plot of VSWR parameters versus frequency of entire design configuration

The proposed antenna has a maximum gain value of 14.55 dBi at 18.52 GHz for the operating band. Table 1 demonstrates that the resonant frequencies, return loss, VSWR values, gain, radiation efficiency are consistent with one another across all operating bands.

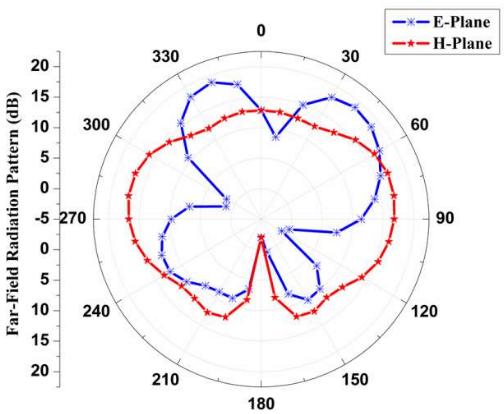
The far-field characteristics of the proposed antenna are illustrated by the radiation patterns, which graphically represent the antenna's radiation properties and are a function of the directional coordinates [17]. Fig. 9 (a-d) shows the radiation patterns of the proposed antenna for the OFF state biased diode condition has resonating at 8.17 GHz, 11.13 GHz, 15.77 GHz, & 17.46 GHz respectively, and Fig. 9 (e-j) represent the radiation pattern for ON state biased diode condition has resonating at 8.38 GHz, 11.13 GHz, 14.51 GHz, 16.20 GHz, 17.46 GHz, 18.52 GHz respectively.



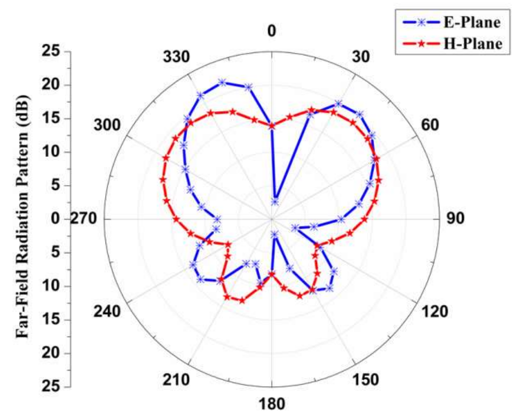
(a)



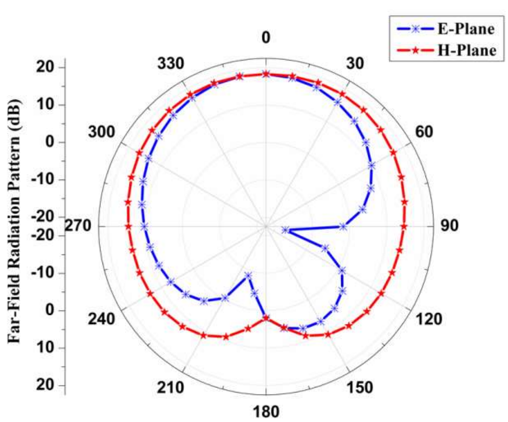
(b)



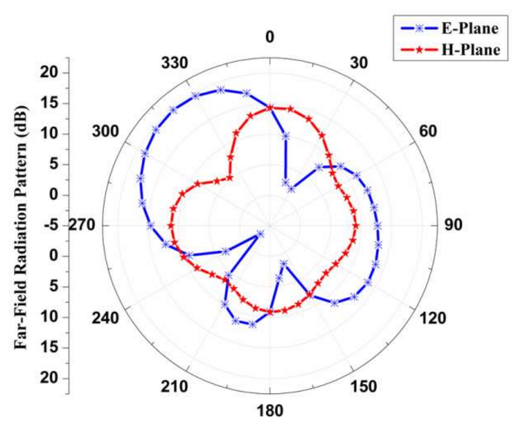
(c)



(d)



(e)



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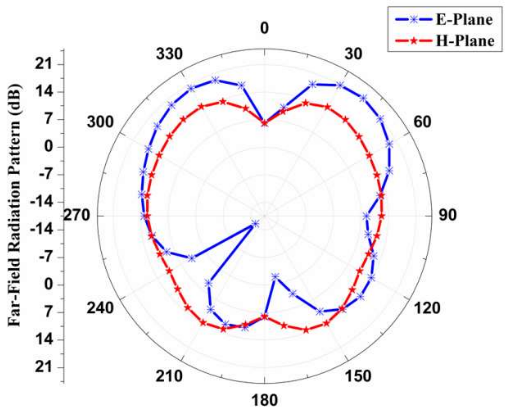
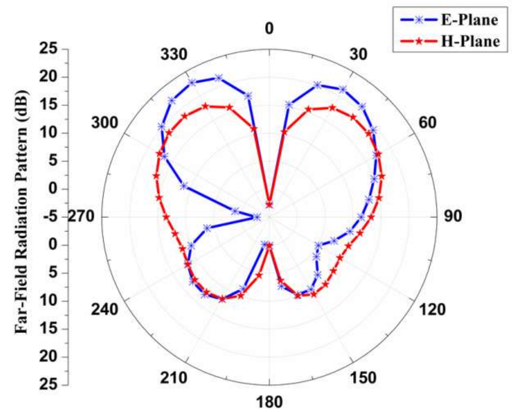
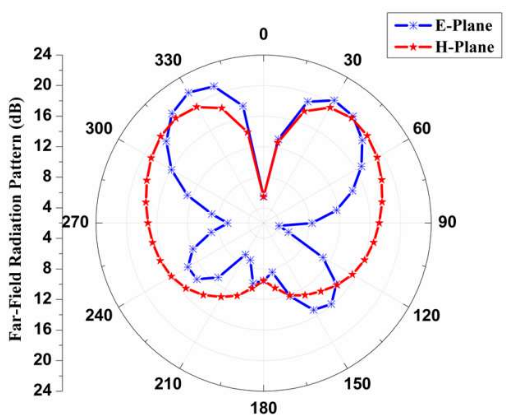


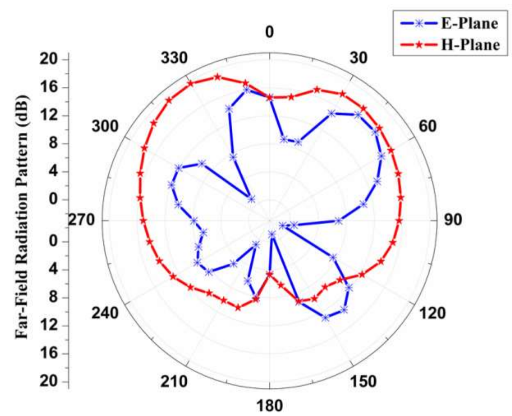
(g)



(h)



(i)



(j)

Fig. 9: Radiation patterns of proposed antenna for diode OFF/ON configurations operated at (a) 8.17 GHz, (b) 11.13 GHz, (c) 15.77 GHz, (d) 17.46 GHz, OFF state and at (e) 8.38 GHz, (f) 11.13 GHz, (g) 14.51 GHz, (h) 16.20 GHz, (i) 17.46 GHz, (j) 18.52 GHz, ON state

The E-plane represents the phi 0º and the H-Plane represents the phi 90º of proposed radiation patterns. The radiation patterns obtained at the resonant frequencies are quite stable and directional. The simulated result shows that these resonant frequencies have a wide range of applications with good gain and radiation pattern throughout the range.

Table 2: Comparative analysis of the proposed work with some literature work

Ref.	**No of band**	**Antenna Size (mm^3)**	**Operating Band (GHz)**	**Antenna Gain (dBi)**	**VSWR**	**Radiation Efficiency (%)**
[11]	2	35×30×1.6	11.35-12.02 13.54-14.30	4.67 3.55	3.96 2.64	NR

[13]	3	28×28×1.57	10.65-12.50 14.68-15.85 17.34-18.32	2.42 1.65 3.64	NR	65.40
[17]	2	70×70×1.6	6.38-9.32 11.55-12.74	2.78 4.87	NR	NR
[18]	2	40×30×1.6	9.65-10.28 14.64-15.76	3.71 2.78	4.52 1.86	72.54
[19]	2	30×30×1.6	13.76-14.67 15.86-16.97	2.95 5.82	NR	NR
[21]	2	30×25×1.57	12.94-13.38 14.94-16.65	3.86 2.75	1.98 2.71	NR
Proposed	4	20×20×1.6	7.96-8.60 10.71-11.55 14.08-15.14 15.56-19.78	13.30 4.67 13.17 14.55	1.52 1.47 1.05 1.95	80.96 85.43 73.36 79.03

Table 2 represents a comparative analysis of the proposed antenna in terms of number of bands, antenna size, operating band, peak gain, voltage standing wave ratio (VSWR), and radiation efficiency. The proposed analysis has received satisfactory response as well as practical applications. Compare ref. [11], [13], [17], [18], [19], and [21] the proposed sizes are small and the obtained results have enhancement and superiority. The proposed gain and radiation efficiency are also increased as compared to the analysis.

4. Conclusion

In the present article, it introduces a novel antenna design that combines a fractal and antenna reconfiguration combined, resulting in a significant performance improvement. The proposed design can change its behavior across multiple bands and low-cost FR4-epoxy substrate material has been used with a simple microstrip feed line which can reduce the implementation cost. The proposed antenna is capable of switching between the operating frequencies in the X-band and Ku-band, exhibiting frequency reconfigurability. This design has potential applications in vehicular communication, satellite communication, and more.

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