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A Design of Multiband Nested Square Shaped Ring Fractal Antenna with Circular Ring Elements for Wireless Applications

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Abstract—This manuscript presents the design of an antenna based on nested square shaped ring fractal geometry with circular ring elements for multi-band wireless applications. The impedance bandwidth and reflection coefficient of the antenna are improved with the design of different iterations from the 0th to 2nd. The performance parameters of the antenna like reflection coefficient, VSWR, bandwidth, bandwidth ratio, and current density are improved in the final iteration. It also achieves the enhanced bandwidth greater than 3 GHz at three resonant frequency bands and exhibits additional frequency band at 2.4 GHz. Likewise, the frequency band of designed fractal antenna shifts towards the lower end and helps in achieving the miniaturization of antenna. The proposed fractal antenna is designed and fabricated on a low-cost FR4 glass epoxy substrate and investigated using HFSS software. The proposed antenna is optimized for generating different parameters, and the last geometry is fabricated and tested. Further, these parameters are compared with the experimental results and found in good agreement with each other. Due to the multi-band behaviour and improved bandwidth, the proposed fractal antenna can be considered as a good candidate for several wireless standards.

1. INTRODUCTION

In the present era, many changes have been noted in correspondence innovation, i.e., guided media is totally replaced by unguided media. These progressive changes are unbelievable without the properly designed structure of an antenna [1]. The most promising antenna in the recent time is fractal antenna, as it is competent to display multiband/wideband behaviour along with scaling down (miniaturization) due to its self-similarity and space-filling properties [2, 3]. Fractal antennas are widely used for the system that needs high data rate and broadband for wideband communications. Nowadays, the growing demand in wireless systems needs compact antenna having wider bandwidth and multiband characteristics with improved reflection coefficient [4, 5]. Fractal antennas are designed by using two properties. Self-similarity means the repetitions of the same structure of antenna at different sizes or scales and space-filling property useful to meet the miniaturization in antenna [6]. Numerous researches have been carried out by the researchers so far in the area of fractal antenna with multiband and wideband characteristics.

Thi et al. [7] proposed a spidron slot based fractal antenna with single feed, triple bands, and circular polarization. Lizzi et al. [8] designed a multiband fractal antenna for wireless communication in an emergency management system. This antenna exhibited an improved impedance matching characteristic in Wi-Fi, WiMAX, and public safety bands. Similarly, Gupta et al. [9] investigated a hexagonal fractal antenna for military applications at frequencies 8.3, 12.6, and 17.6 GHz. Singhal et al. [10] investigated a fractal antenna based on elliptical monopole for super wideband applications. A triple band microstrip fractal antenna was designed by Barreto and Mendonca [11] for C- and S-band applications. Dastranj et al. [12] designed a compact circular shape fractal antenna for broadband wireless communication applications. This antenna is useful for the operation in S, C, X, and Ku bands.

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In this design, the fractal geometry of radiating antenna uses an iterative circular patch with a square slot, an altered feed-line with step method, and slot-loaded semi-circular ground plane to get a wide impedance bandwidth. Salucci et al. [13] designed a multiband fractal antenna using system by system method for NB-IoT applications. A fractal antenna for multiband applications in the frequency bands of 1.86, 2.29, 3.02, and 4.50 GHz was designed by Yogamathi et al. [14]. Sidhu and Sivia investigated a novel fractal antenna [15] for wireless applications in S, C, and X band standards. Kaur et al. [16] designed an antenna based on a hexagonal ring-shaped patch with staircase fractal geometry for distinct wireless standards. This antenna exhibits dual frequency bands with bandwidth of 7.74 GHz and maximum gain of 6.99 dB. Rahman et al. [17] designed a small size, UWB (Ultra-Wide Band), band-notched antenna with integrated Bluetooth for UWB and personal wireless communication applications. It works at the UWB frequency (3.1–10.6 GHz) as well as Bluetooth (2.4–2.484 GHz), with band-notch quality at the WLAN frequency (5–6 GHz) band. Khan and Rahman [18] developed an inverted G-shaped frequency reconfigurable antenna by inserting two PIN diodes in vertical and horizontal strips. Multiple reconfigurable operational frequency bands were achieved in the frequency range of 3 GHz to 10 GHz. It is useful for WLAN, Long-Distance Radio Telecommunications, WiMAX, and X-band Satellite Communication applications. Ahmad et al. [19] reported a meandered radiator based monopole antenna for WiMAX and WLAN applications. Rahman et al. [20] presented an efficient method for reducing the time-domain ringing in a UWB antennas. Khan et al. [21] presented a CPW-fed, tripleband frequency reconfigurable antenna for wireless applications.

This manuscript proposes a fractal antenna design using a square ring structure and a set of three circular rings attached to all the four sides of the square ring to generate the desired antenna structure. Further, using the scaling and self-similar method, the other iterations of antenna are designed to get the multiband characteristics and wider bandwidth. The impedance bandwidth of the antenna is improved with the design of different iterations from the 0th to 2nd. The detailed design process of proposed antenna and its various performance parameters along with antenna optimization are discussed in Sections 2 and 3.

2. ANTENNA DESIGN PROCESS

2.1. Design Evolution of Proposed Fractal Antenna

The proposed antenna design initiates with a square ring having side length Y_1 ($L \times W$) and thickness of 1 mm. The antenna is designed on an FR4 glass epoxy substrate of thickness 1.6 mm and dielectric constant 4.4 with the designed frequency of 4.6 GHz. By using all these data, the side length of the square ring patch has been evaluated by using the following equations and is found to be 15 mm.

Width (W) of rectangular shaped radiating patch is evaluated by using Equation (1)

$$w = \frac{c}{2f_r\sqrt{\dfrac{\varepsilon_r + 1}{2}}} \tag{1}$$

The effective dielectric constant of the substrate is computed by using Equation (2)

$$\varepsilon_{reff} = \left[\frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\right]\frac{1}{\sqrt{1 + 12h/w}}, \quad 1 < \varepsilon_{reff} < \varepsilon_r \tag{2}$$

Extended incremental length (ΔL) of the proposed antenna is obtained by using Equation (3) as shown below. Now the total length (L) of radiating patch is computed with the help of Equation (4) as given below, where $1/\sqrt{\mu_o}\varepsilon_o$ is the speed of light in vacuum.

$$\Delta L = h * 0.412\left[\frac{(\varepsilon_{reff} + 0.3)\left(\dfrac{W_P}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\dfrac{W_P}{h} + 0.8\right)}\right] \tag{3}$$

$$L = \frac{1}{2f_r\sqrt{\mu_o}\varepsilon_o\sqrt{\varepsilon_r}} - 2\Delta L \tag{4}$$

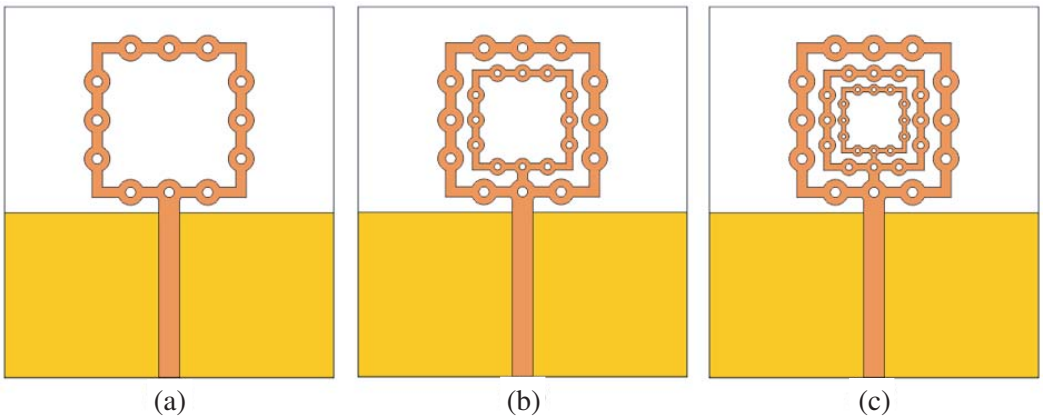

Figure 1. Design evolution of proposed fractal antenna: (a) 0th iteration, (b) 1st iteration and (c) 2nd iteration (proposed antenna).

Further, the circular ring is designed with outer radius 1.25 mm and inner radius 0.5 mm. Then this ring is copied, and a set of three rings are attached to all the four borders of the square ring as delineated in Fig. 1(a) and designated as the 0th iteration of the designed antenna. To analyze the performance of the designed structure, a 50 Ω transmission line with length 'L_3' and width 'W_3' is employed with partial ground plane '$L_2 \times W_2$' in the geometry of the 0th iteration. The partial ground plane is used in this structure for better impedance characteristics and bandwidth. Moreover, to generate the other iterations (1st and 2nd) of the designed fractal antenna, the structure of patch designed in the 0th iteration is copied and scaled down to 66% from its original dimension on the basis of the same pattern as in the case of Koch fractal curve. After performing the scaling process, the obtained geometry is attached to the structure of the 0th iteration to get the 1st iteration of the proposed antenna as delineated in Fig. 1(b). Likewise, this step is again used to get the 2nd iteration of the proposed antenna (final structure) as shown in Fig. 1(c).

All the structures (0th to 2nd iterations) of the proposed antenna are designed on a low-cost FR4 glass epoxy substrate having thickness 1.6 mm, dielectric constant 4.4, mass density 19,000 kg/m^3, and 0.02 loss tangent. The last optimized geometry of the antenna delineated in Fig. 2 and Table 1 shows the optimized parametric dimensions of the antenna.

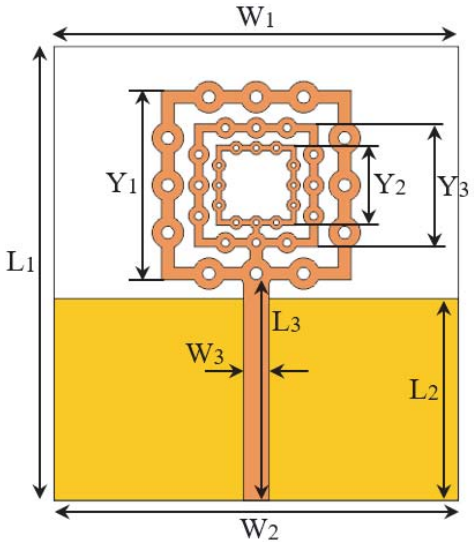

Figure 2. Optimized parametric geometry of proposed antenna.

Table 1. Parametric values of designed antenna.

Parameters	Values (mm)	Parameters	Values (mm)
W_1	32	L_3	17.25
L_1	36	Y_1	15
W_2	32	Y_2	9.75
L_2	16	Y_3	6.33
W_3	2.0		

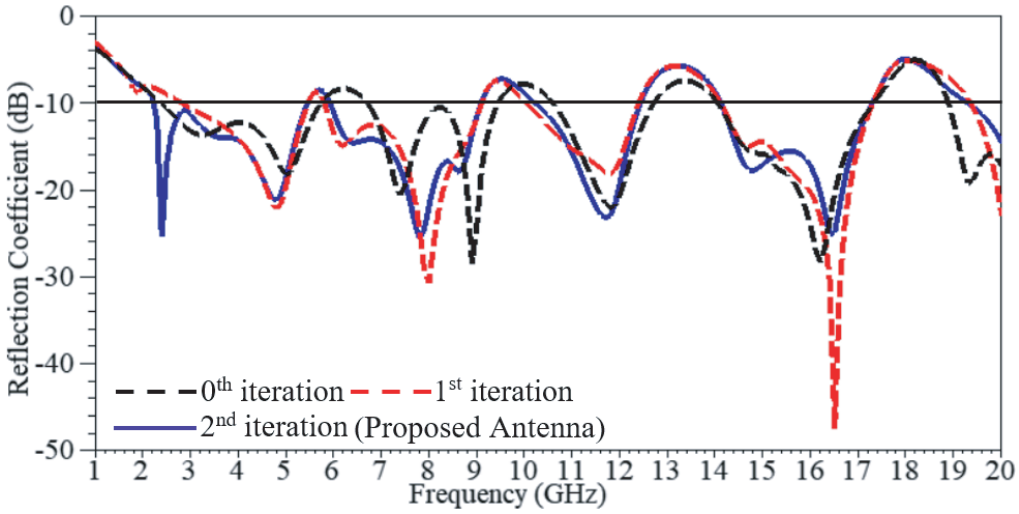

Figure 3. Reflection coefficient curve for different iterations of designed antenna.

Figure 3 illustrates the reflection coefficient plot for all the iterations of designed antenna. It shows that for all the iterations, antenna exhibits five distinct frequency bands. On the comparison of the reflection coefficients of the 0th and 1st iterations, it is clear that the bandwidth of antenna has increased from 2.75 GHz to 3.29 GHz in the second and third frequency bands due to the increase in perimeter in the 2nd iteration with addition of fractal element. Further, in final iteration (2nd iteration), the 1st resonant frequency band has been shifted towards the lower side from 4.8 GHz to 2.4 GHz without affecting the bandwidth of other frequency bands in comparison to previous iteration. This shifting of the frequency band is due to the self-similarity property of the fractal antenna used in the successive iterations of the proposed antenna. The shifting of frequency band to the lower side results in achieving the miniaturization of antenna. The proposed antenna is also analysed with and without circular elements as the structure shown in Fig. 4, and the reflection coefficient plots for both are shown in Fig. 5. It can be concluded that an antenna with circular elements exhibits wider bandwidth than an antenna without circular elements at all the frequency bands. Thus, an improvement in performance parameters of the designed antenna has been seen as compared to the other iterations. The results of all the consecutive iterations are illustrated in Table 2 for more clarity.

2.2. Effects of Ground Plane Length 'L_2' on the Performance of Antenna

The parametric analysis for the length of partial ground plane 'L_2' has also been studied to get better results in terms of frequency bands and impedance bandwidth. 'L_2' parameter is varied from 14 to 16 mm with an increased step size of 1.0 mm as shown in Fig. 6. It is clear from it that the length of partial ground plane plays a very important role in the betterment of antenna performance parameters. Firstly, the length of the ground plane is taken as 14 mm, and it is observed that the antenna resonates only at two frequency bands 3.3 and 7.8 GHz with corresponding reflection coefficients of −20.69 dB and

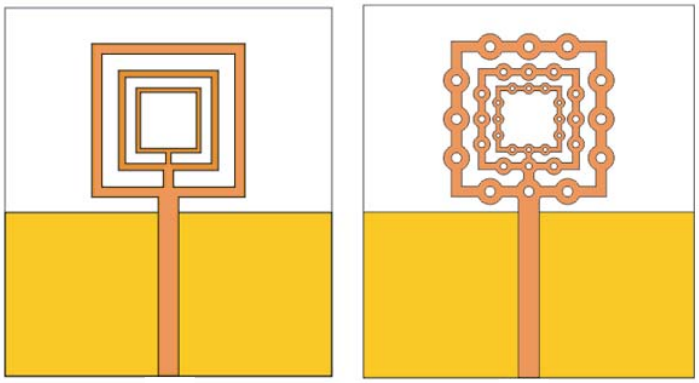

Figure 4. (a) Antenna without circular elements and (b) antenna with circular elements (Proposed).

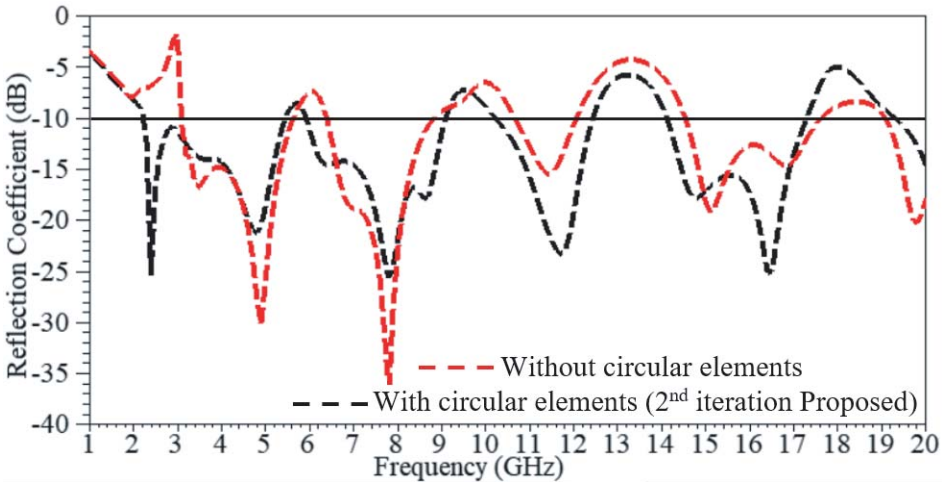

Figure 5. Reflection coefficient curve for the different structures of proposed antenna.

−11.37 dB. Similarly, with increase in the length by 1.0 mm, the antenna again exhibits two frequency points at 4.8 and 7.7 GHz with corresponding reflection coefficients of −21.61 dB and −17.10 dB. Though the antenna with 'L_2 = 15 mm' exhibits only two frequency points, the improvement in reflection coefficient has been noted at both the frequency bands. In spite of these, the other two frequency bands are observed at 11.6 and 16.9 GHz with less reflection coefficient. So, finally the value of 'L_2' is taken as 16 mm, and it is reported that the antenna reveals five distinct frequency bands 2.4, 4.8, 7.8, 11.7, and 16.5 GHz with improved reflection coefficient and impedance bandwidth at respective frequency bands. From the above parametric study, the optimum value of 'L_2' is fixed as 16 mm for the better performance of the proposed antenna.

2.3. Surface Current Distribution

Figure 7 shows the current distribution on the surface of both sides of the proposed antenna at different frequency bands. It shows that current distribution has concentrated on the outer fractal ring along with the transmission line at 2.4 and 4.8 GHz frequency points. Similarly, the current is concentrated at the outer and inner fractal rings along with partial ground plane and transmission line at higher frequency points (7.8, 11.7 and 16.4 GHz). The strong current distribution on the surface of the proposed fractal antenna helps in generating wider bandwidth and more frequency bands.

Table 2. Comparison of results for different iterations of proposed fractal antenna.

Antenna Design	Operating frequency band (GHz)	Lower frequency F_L (GHz)	Upper frequency F_U (GHz)	Bandwidth (GHz)	Bandwidth Ratio
0th iteration	5.0	2.39	5.74	3.31	2.40 : 1
	7.4	6.70		2.75	1.41 : 1
	8.9		9.45		
	11.8	10.60	12.71	2.11	1.19 : 1
	16.2	14.04	17.32	3.28	1.23 : 1
1st iteration	4.8	2.80	5.47	2.67	1.95 : 1
	6.2	5.81		3.29	1.56 : 1
	8.0		9.10		
	11.8	10.05	12.39	2.34	1.23 : 1
	16.5	14.11	17.30	3.19	1.22 : 1
2nd iteration (Proposed Antenna)	2.4	2.23	5.46	3.23	2.44 : 1
	4.8	5.92		3.17	1.53 : 1
	7.8		9.09		
	11.7	10.22	12.43	2.21	1.21 : 1
	16.5	14.11	17.29	3.18	1.22 : 1

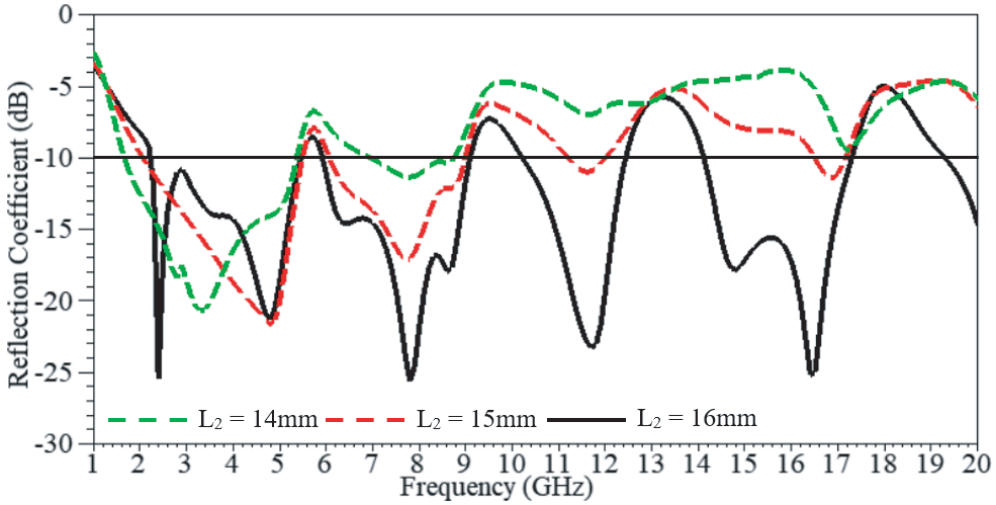

Figure 6. Reflection coefficient curve for the variations in length of partial ground plane.

3. PROTOTYPE AND RESULTS

Figure 8 reports the front and back views of the antenna. The results of the antenna have been measured using the vector network analyser (VNA) for different performance parameters such as reflection coefficient and radiation pattern. Fig. 9 illustrates the comparison of simulated and experimentally measured reflection coefficients of the proposed fractal antenna. This fabricated antenna exhibits the frequency bands of 2.6, 4.7, 7.9, 11.8, and 16.5 GHz which are quite similar to the simulated ones, and these results are in good agreement with each other. A small variation in these results is due to the soldering bumps, environmental conditions, physical properties of fabricated prototype, connector

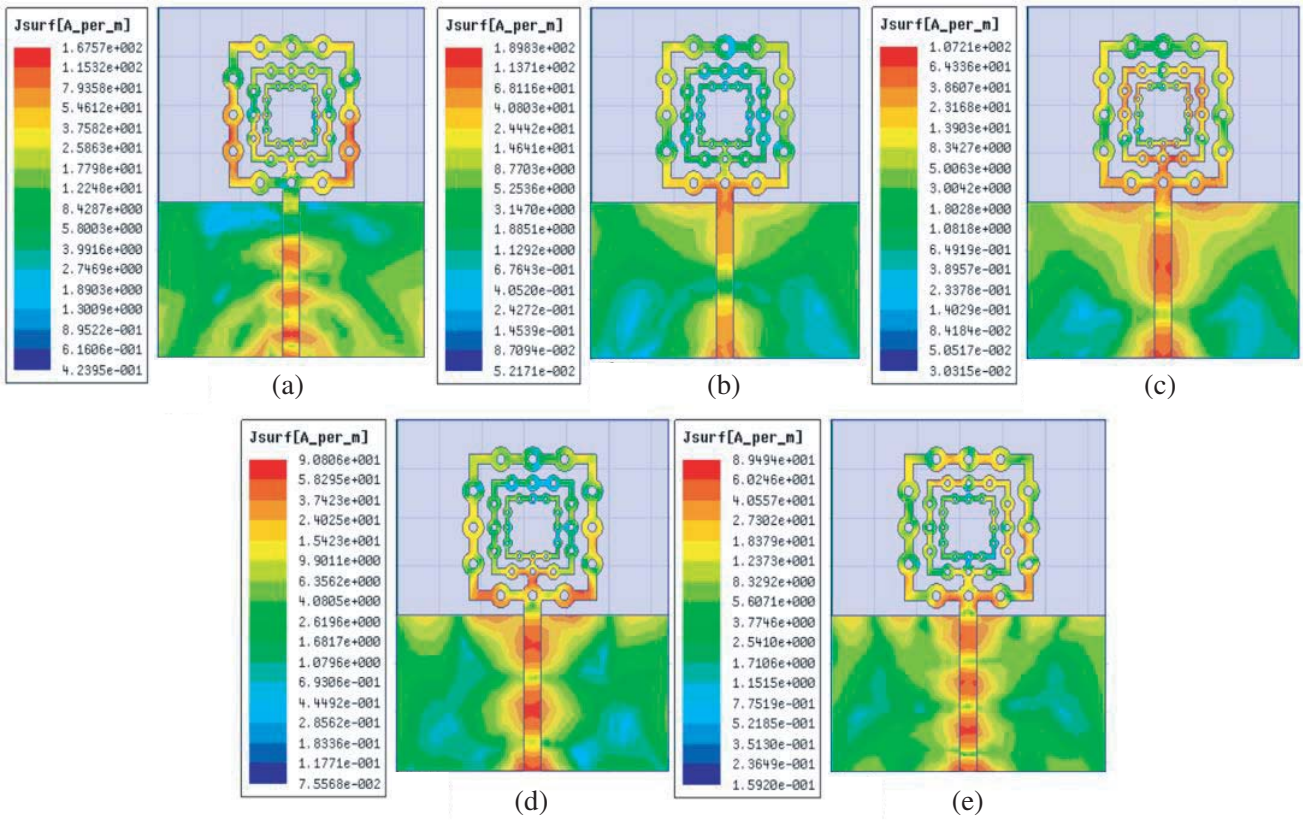

Figure 7. Surface current distribution of proposed antenna at (a) 2.4, (b) 4.8, (c) 7.8, (d) 11.7 and (e) 16.4 GHz frequency bands.

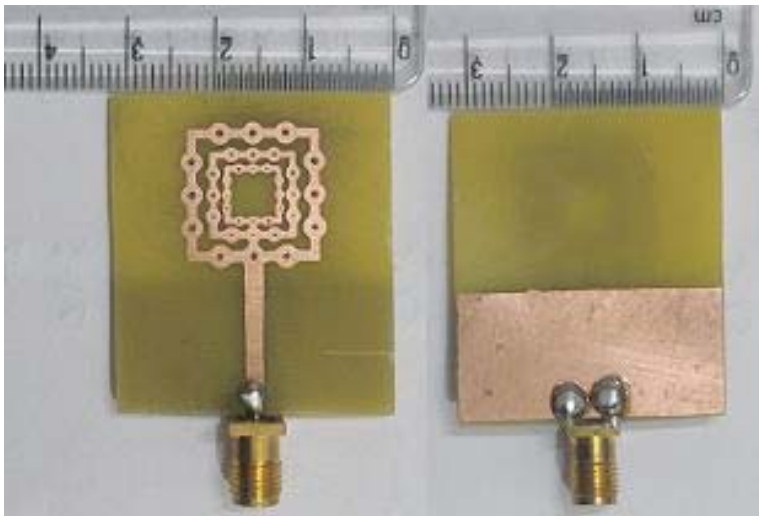

Figure 8. Front and back view of fabricated structure of proposed fractal antenna.

losses, etc. Fig. 10 shows the radiation patterns in E- and H-planes for the proposed fractal antenna at different frequency bands. The red and black lines show the pattern in E-plane, whereas blue and green lines show the pattern in H-plane. It shows that proposed antenna exhibits bidirectional and omnidirectional radiation patterns in E- and H-planes for 2.4, 4.8, and 7.8 GHz resonance points. The radiation patterns at other frequency bands 11.7 and 16.5 GHz are slightly distorted in both the planes

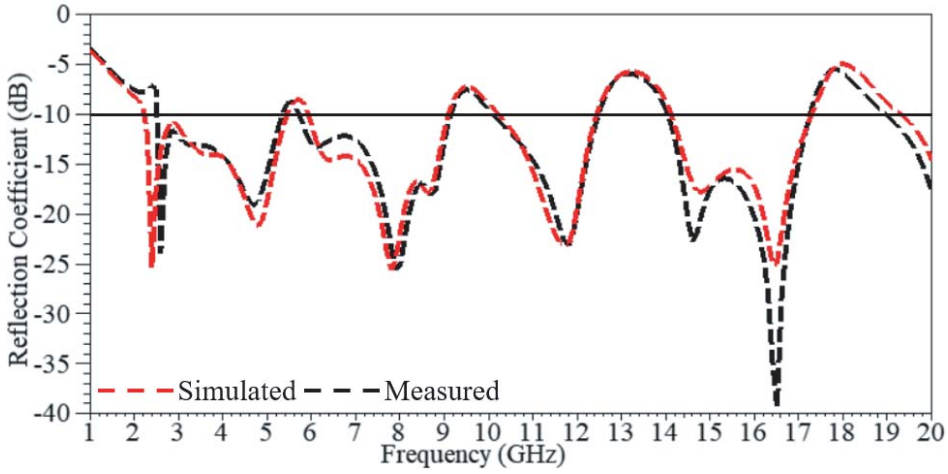

Figure 9. Comparison of simulated and measured reflection coefficient of proposed antenna.

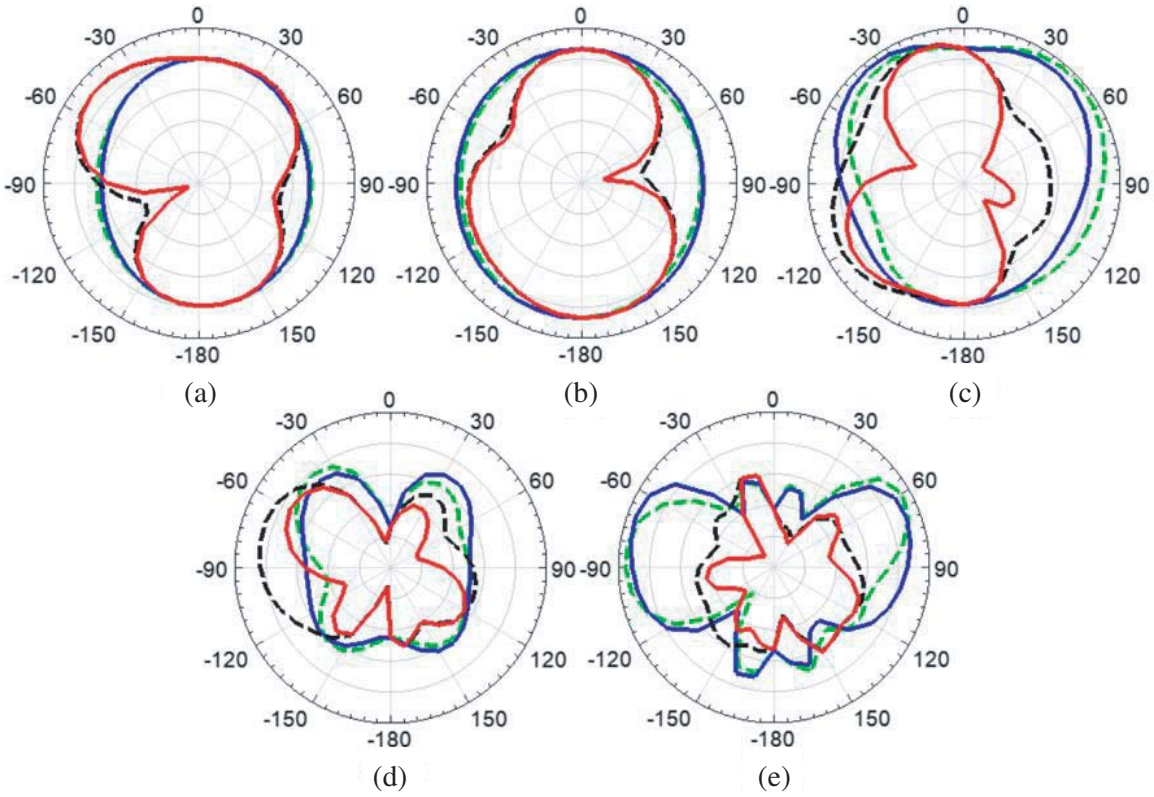

Figure 10. Radiation pattern of proposed antenna at (a) 2.4, (b) 4.8, (c) 7.8, (d) 11.7 and (e) 16.4 GHz frequency bands (solid line: simulated and dashed line: measured).

due to higher order modes and the distribution of short wavelength differentiated electric current on the surface of proposed fractal antenna.

The assessment of the proposed fractal antenna with other existing fractal antennas is tabulated in Table 3. From Table 3, it can be observed that the antennas designed in [22, 23, 28–30] are compact in size as compared to the proposed fractal antenna. However, these antennas have less frequency bands and bandwidth than the proposed fractal antenna. Due to the higher number of frequency bands and more impedance bandwidth, the proposed fractal antenna is useful for different wireless applications

Table 3. Assessment of proposed fractal antenna with other existing antennas.

Author	Size of antenna (mm^2)	Resonant frequency band (GHz)	Maximum bandwidth
[22]	30×40	2.55/3.66/5.28	1.4 GHz
[23]	30×38	1.92/3.10	680 MHz
[24]	38×38	0.92	5 MHz
[25]	45×45	3.0/5.0/6.8/7.5/8.5	200 MHz
[26]	40×46	2.45	100 MHz
[27]	40×40	2.5	1.8 GHz
[28]	32×38	2.55/3/5/6.5	1.15 GHz
[29]	21×21	0.921	13 MHz
[30]	30×31	2.5/3.5/5.2	–
Proposed Antenna	36×32	2.4/4.8/7.8/11.7/16.5	3.23 GHz

such as LTE 2300/LTE 2500 (2.3–2.4 GHz/2.5–2.69 GHz), Bluetooth (2.4 GHz), WLAN (2.4–2.48, 5.15–5.35 GHz), WiMAX (3.3–3.7 GHz), ITU band (7.8–8.4 GHz), television broadcasting (7.91–8.62 GHz, point-to-point wireless applications (5.92–8.5 GHz), FSS (11.45–11.7 GHz), defence systems (14.62–15.23 GHz), and aeronautical radio navigations (15.43–17.3 GHz).

4. CONCLUSION

Fractal antenna based on a square ring structure using circular ring elements is designed for multiband wireless applications in this manuscript. Three iterations of antenna have been designed, investigated, and observed. The last iteration (2nd) shows improved results in terms of impedance bandwidth. The improvement in bandwidth and multiband characteristics of the proposed fractal antenna makes it useful for different wireless standards such as LTE 2300/LTE 2500, Bluetooth, WLAN, WiMAX, ITU band, television broadcasting, point-to-point wireless applications, FSS, defence systems, and aeronautical radio navigations.

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