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A Miniaturized Fractal Antenna with Square Ring Slots for Ultrawideband Applications

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Abstract—In this paper, a low-profile fractal antenna with square ring slots is reported. The newly proposed fractal antenna includes circular ring radiating elements with orthogonally placed square shape slots to achieve ultra-wideband operation. The compact antenna ($32 \times 28 \times 1.6\,\text{mm}^3$) is designed and fabricated on an FR4 dielectric substrate, and measurements are performed to validate the simulation results. The simulated and measured results demonstrate that the antenna has -10 dB impedance bandwidth of 9.4 GHz from 4.2 to 13.6 GHz in the ultra-wideband frequency. The measured results reveal that the antenna has omnidirectional radiation characteristics with peak gain of 5 dB in the desired band of operation. The proposed antenna has low cross polarization of -28 dB and radiation efficiency about 88% in the operating bandwidth. The large bandwidth, low cross polarization, and stable radiation characteristics confirm that the proposed antenna may be suitable for ultra-wideband applications.

1. INTRODUCTION

Today, ultra-wideband (UWB) technology has achieved increased demand in the field of wireless communication because of several attractive features such as low power consumption, high speed operation, low interference, and high resolution. Further, this technology gained increased popularity when UWB was given access for commercial applications, namely Wi-Fi, WiMAX, and WLAN [1]. Since the antenna is a key element in these systems which determine the performance in terms of capacity, data rate, and efficiency, an antenna with good radiation characteristics, low cross polarization, and large bandwidth has become a research hotspot in the applications such as wireless portable devices, radars, and remote sensing [2, 3]. Several antennas have been designed and employed for UWB applications, typically Vivaldi antenna [4], horn antenna [5], spiral antenna [6], and log periodic antenna [7]. Though wide bandwidth, high gain, and antenna with good radiation characteristics have been realized, in the recent days, the antenna based on fractal theory has become the centre of attraction due to several advantages including size reduction, multi-band operation, and uniform repeatability. Fractal geometries are widely used in antenna miniaturization due to their space filling, self scaling, and self-similarity properties. The space-filling property results in electrically large size features while the self-scaling property uses similar shapes of multiple scales. The self-similar property enables the use of iteration function with similar shapes. According to the fractal geometry principle, an efficient miniaturized antenna design is possible when the conducting element is repeated such that the entire length of the antenna remains same, but the antenna size is reduced [8]. The fractal geometry when being combined with a microstrip antenna structure leads to the development of fractal antennas. Usually, the fractal geometries comprise irregular shape radiating elements designed evenly into sub-parts etched on a

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dielectric substrate resulting in the fractal antenna. Fractal antennas are mainly employed in wireless systems, satellite, and military systems.

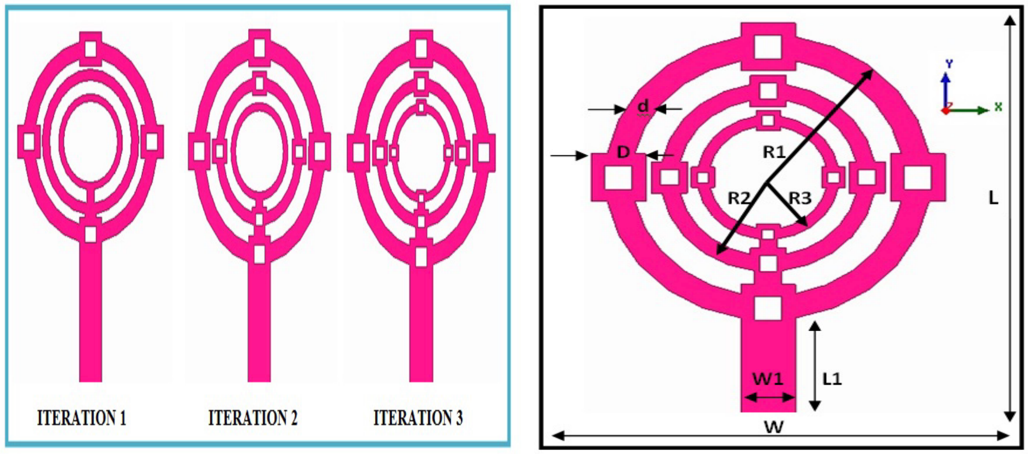
In recent days, considerable research has been performed on the design and analysis of fractal antennas. Several reports have been presented with different sizes, shapes, and geometries in the open literature. In [9], a multiband hybrid fractal antenna ($45 \times 38.92 \times 1.6\,\text{mm}^3$) designed on an FR4 substrate is reported. This structure resonates at five different frequencies which makes the antenna suitable for point to point communication, C and X band applications. The peak gain of 2.84–7.56 dB has been realized at the resonating frequencies. A microstrip printed antenna ($170 \times 70 \times 6\,\text{mm}^3$) with log-periodic square fractal geometry for ultrawideband applications is presented in [10]. Using this structure, an overall size reduction of 23% has been realized, and the antenna has an impedance bandwidth of 7.5 GHz ranging from 3.1 to 10.6 GHz. The antenna provides a peak gain of 8 dBi and overall efficiency of 80% in the desired band of operation. However, broadside radiation pattern and high cross polarization limit the applications of antenna. The antenna presented in [11] is a compact antipodal Vivaldi antenna ($56 \times 50 \times 0.8\,\text{mm}^3$) printed on an FR4 dielectric substrate for ultra-wideband applications. This structure implements a sinusoidally modulated Gaussian tapered slot and bending feed structure to achieve ultra-wideband operation. Using this structure, an impedance bandwidth of 10 GHz from 2 to 12 GHz and peak gain of 1.5–5.2 dBi have been achieved in the whole frequency band. Besides, the antenna adopts a complex feed network and has high cross polarization. Soni and Singhai [12] presented a multiband hybrid fractal antenna ($90 \times 75 \times 1.6\,\text{mm}^3$) printed on an FR4 substrate with a Minkowskized radiating structure. This structure resonates at six different frequencies suitable for GSM, Wi-MAX, Wi-Fi, and WLAN applications. In [13], a circularly shaped fractal antenna ($70\,\text{mm} \times 70\,\text{mm} \times 1.57\,\text{mm}$) printed on an RT Duroid 5880 substrate for ISM band application is reported. The antenna structure is implemented by rotating the square patch at a specified angle. The structure has an impedance bandwidth of 50 MHz at a center frequency of 2.5 GHz and peak gain of 7 dBi in the operational frequency band. Besides, low bandwidth and unstable radiation patterns are the primary limitations of the structure. A hexagonal fractal antenna ($25\,\text{mm} \times 30\,\text{mm} \times 0.8\,\text{mm}$) printed on an FR4 substrate with triangular elements is investigated in [14]. The antenna operates over 3–25.2 GHz frequency band and provides a fractional bandwidth ratio of 8.4 : 1. The peak gain of the antenna varies from 3 to 9.8 dBi in the whole frequency band. A multipurpose fractal antenna compatible with Bluetooth, GSM, Wi-Fi, GPS, and Wi-MAX is presented in [15]. The antenna adopts ground optimization technique with a trident shape fractal geometry and electromagnetic band gap structure to achieve multiband characteristics. An impedance bandwidth of 1.59–13.31 GHz and peak gain of 2.52 dBi have been realized. The low realized gain and complex design structures are the major limitations of the design. The antenna in [16] adopts a Koch fractal boundary and quadratic fractal slot to achieve band rejection characteristics. The antenna is designed on an FR4 substrate and has an overall size of $18.5\,\text{mm} \times 39\,\text{mm} \times 1.59\,\text{mm}$. The antenna operates over 3.2–12 GHz with a notch band at 5.5 GHz. The antenna provides a peak gain of 4 dBi in the whole frequency band of operation. However, high cross polarization and low efficiency are the major drawbacks of the structure.

2. FRACTAL ANTENNA DESIGN

Conventionally, the design of a fractal antenna is based upon iterative procedure. The primary objective of the design is to increase the path length of the surface current over a large surface area (a long length) developed in a limited volume or space. This results in multi-band or ultra-wideband operations due to the self-similarity behavior. The evolution of the proposed antenna and its geometry are shown in Figures 1(a) and (b).

As shown in Figure 1(a), the antenna consists of nested circular rings with square shaped slots to achieve ultra-wideband operation. The nested circular radiating elements along with orthogonally placed square shaped slots form the fractal geometry. In the first iteration, an outer circle ring of radius $R1$ and thickness d is designed. Then four orthogonal square shaped slots are added into the design. In the second iteration, another circular ring of radius $R2$ along with square slots is introduced adopting the fractal geometry. Finally, in the third iteration, the inner circle of radius $R3$ is designed to complete the antenna structure.

The following equations are used to determine the fractal geometry given as:



(a) (b)

Figure 1. (a) Step-by-step iteration, (b) geometry of fractal antenna.

The radius R of circular ring is given by:

$$R = \frac{M_{11C}}{5.714 f_r \sqrt{\varepsilon_{eff}}} \tag{1}$$

$$D = 1.25d \tag{2}$$

$$d2 = 0.5d \tag{3}$$

$$d3 = 0.25d \tag{4}$$

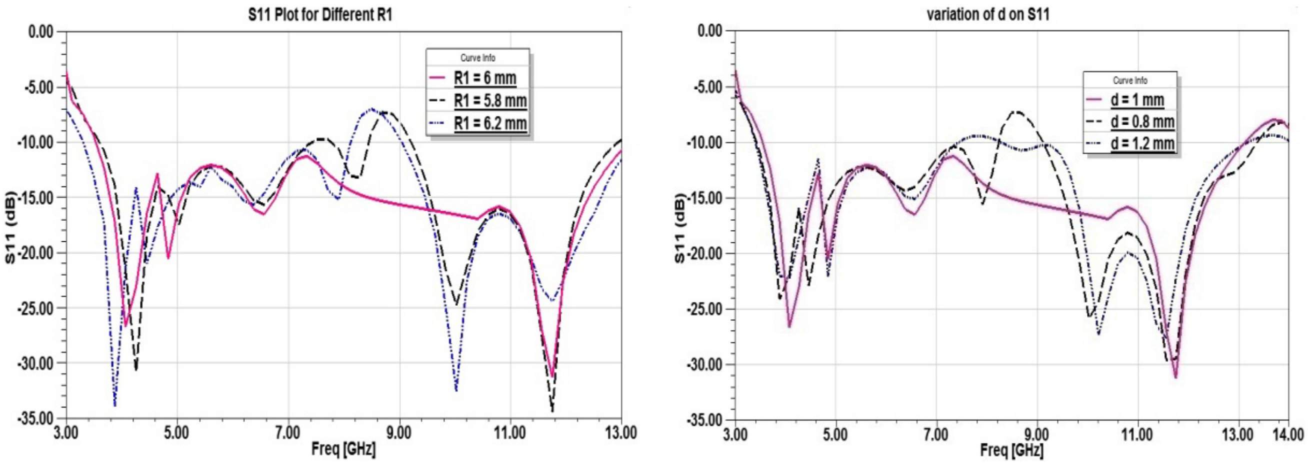
where R is the radius, M_{11} the propagation mode constant, C the free space velocity (m per sec), f_r the resonant frequency (GHz), and ε_{eff} the effective permittivity of the substrate. D is the size of square slot, and d is the thickness of the circular ring. The width of the middle and inner circles, $d2$ and $d3$, respectively are chosen as given in Eqs. (3) and (4) for large bandwidth. In the presented work, the value of M_{11} is selected as 1.841 in the TM_{11} mode for better performance. The overall size of the proposed antenna is 32 mm × 28 mm with a substrate thickness of 1.6 mm which are determined by parametric analysis.

3. PARAMETRIC ANALYSIS

To achieve wide-band characteristics with low cross polarization, the optimized dimensions of the proposed antenna are realized by parametric study using Ansys High-frequency structure simulator software. Several antenna parameters, typically outer circle radius ($R1$), width of circular ring (d), fractal ratio (combinations of $R2$ and $R3$), are varied, and antenna performance is analyzed. The return loss plot for different values of $R1$ is depicted in Figure 2(a). The results show that the proposed structure has −10 dB impedance bandwidth of 9.4 GHz over 4.2–13.6 GHz for $R1 = 6$ mm. It is seen that the antenna exhibits notch characteristics over 8–9.2 GHz for $R = 5.8$ mm and 6.2 mm.

The effect of width of the circular ring (d) on return loss is plotted in Figure 2(b). It can be seen that for $d = 1$ mm, the return loss is less than −10 dB in the whole band of frequency while notch band is introduced over 8.4–9 GHz for $d = 0.8$ mm.

The return losses for different fractal ratios are shown in Figure 3. It is evident that the return loss is less than −10 dB from 4.2–13.6 GHz for $R2 = 0.72R1$ and $R3 = 0.436R2$, i.e., $R3 = 0.3139R1$, which is nearly equal to 32% of base radius $R1$ of the circular ring. Thus, it is established that the overall size of the antenna is reduced by nearly 32%. Therefore, from these studies, it is established that the self similarity property of the fractal iterations and increased electrical length provide wide impedance bandwidth. The optimized dimensions of the antenna determined from the parametric studies are given in Table 1.



(a) (b)

Figure 2. (a) S_{11} plot for different values of $R1$, (b) S_{11} plot for different circular ring width d.

Table 1. Optimized dimensions of the antenna.

parameter	Size (mm)	parameter	Size (mm)
W	28	$R1$	6
L	32	$R2$	4.32
t	1.6	$R3$	1.9
$W1$	2	d	1
$L1$	17.34	D	1.55

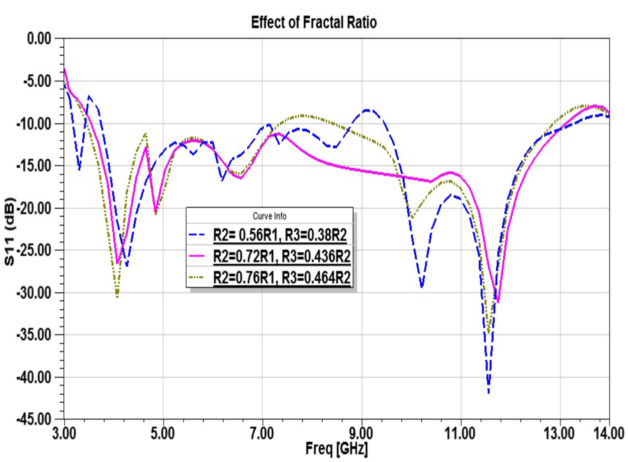


Figure 3. S_{11} plot for different fractal ratios.

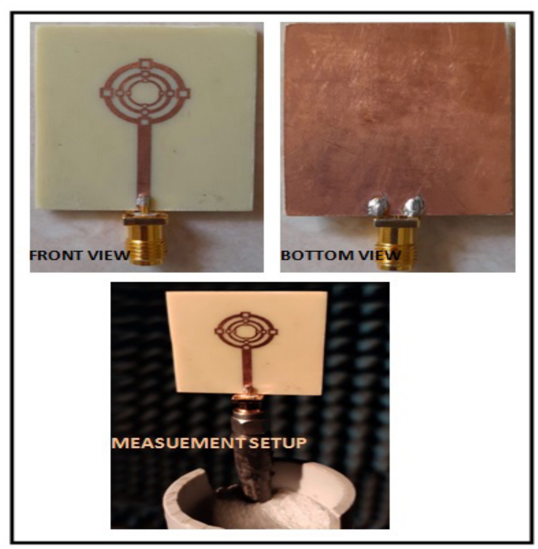


Figure 4. Photograph of prototype (front and bottom view) and measurement setup.

A prototype of the antenna is fabricated on an FR4 substrate with dielectric constant (ε_r) 4.4 and thickness 1.6 mm. The photograph of the antenna and measurement setup is shown in Figure 4. A 50 Ω SMA connector is used as an antenna port. Various antenna parameters, typically return loss S_{11}, radiation patterns, and peak gain, were measured using Keysight N9918A vector network analyzer, and simulation results were validated.

4. RESULTS AND ANALYSIS

The return losses of the proposed antenna for three different iterations are plotted in Figure 5. It is noted that the return loss of the final design spans over 9.4 GHz ranging from 4.2–13.6 GHz. The results establish that the self similarity property of the fractal iterations provides large bandwidth.

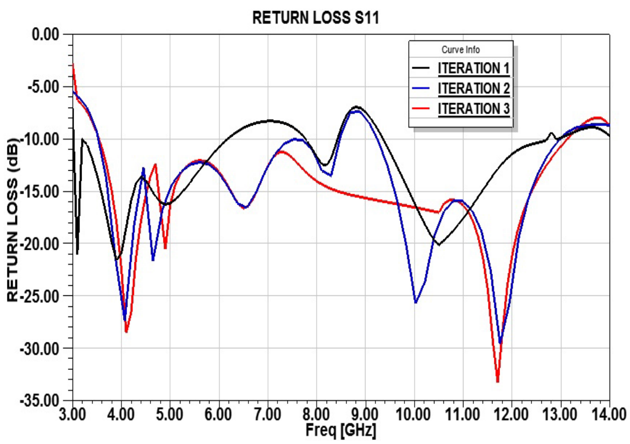


Figure 5. Return losses for different iterations.

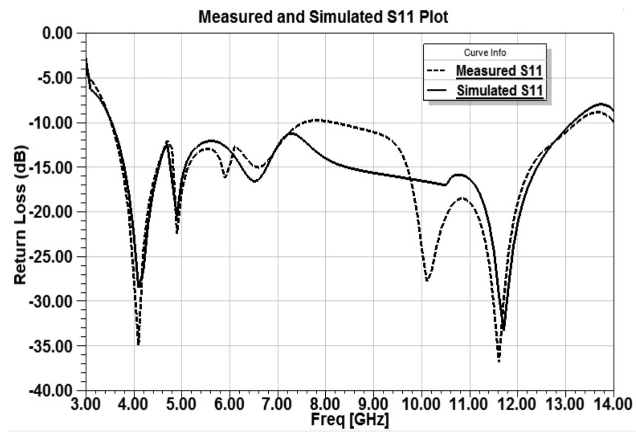


Figure 6. Measured and simulated S_{11}.

The measured and simulated return losses of the final structure are depicted in Figure 6. It is obvious that the measured and simulated results agree well over the operating frequency band. However, the small differences may be due to defects in fabrication and measurement errors.

4.1. Surface Current Distribution

The operating principle of the antenna can be explained referring to current distribution as shown in Figure 7. It can be seen that the current is concentrated along the feed line at 6.8 GHz. At higher frequencies, most of the current flows at the outer and inner rings, typically at 8.4, 10.6, and 11.8 GHz. The strong current distribution on the surface of the antenna results in wider bandwidth and good radiation patterns.

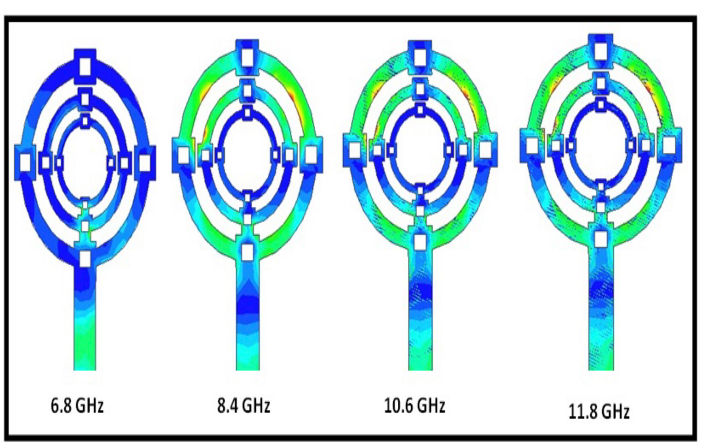


Figure 7. Current distribution at 6.8, 8.4, 10.6 and 11.8 GHz.

4.2. Radiation Patterns

The simulated (solid line) and measured (dotted line) radiation patterns at frequencies 6.8, 8.4, 10.6, and 11.8 GHz are plotted in Figure 8. It is obvious that the antenna has omnidirectional radiation patterns both in E and H planes. However, tilt in radiation pattern at higher frequencies is observed which may be due to the effect of higher mode at higher frequencies of operation.

Further, the directivity behavior of the antenna is analyzed in terms of co-polarization and cross-polarization as shown in Figure 9 and Figure 10. It is revealed that the cross-polarization as low as −28 dB is realized with a cross-polarization to co-polarization ratio of 6 dB.

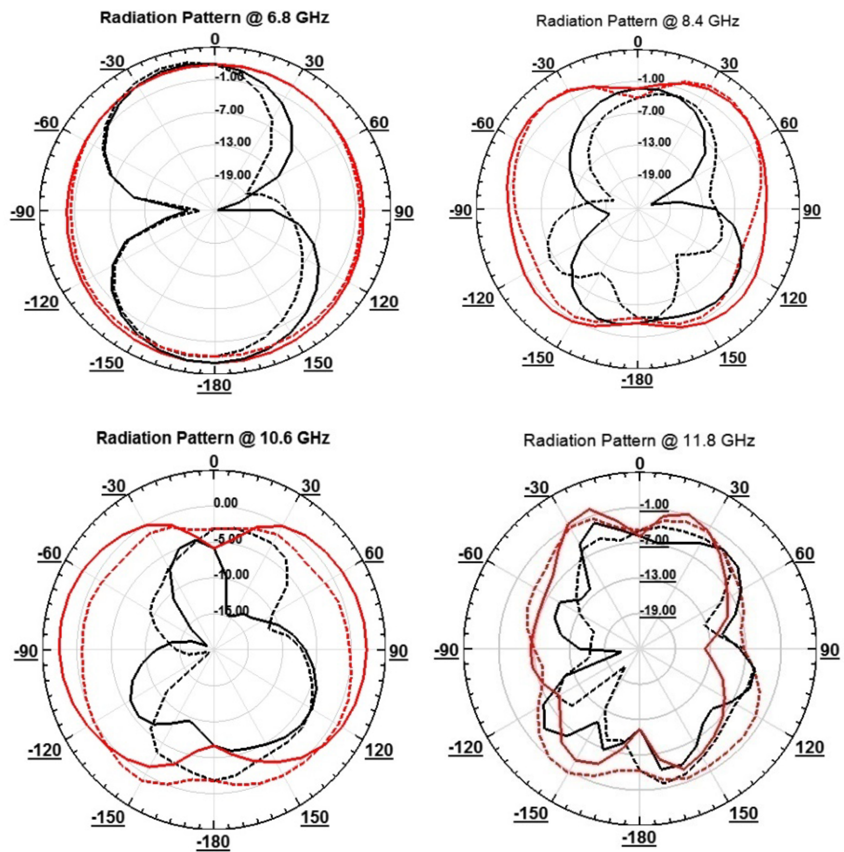
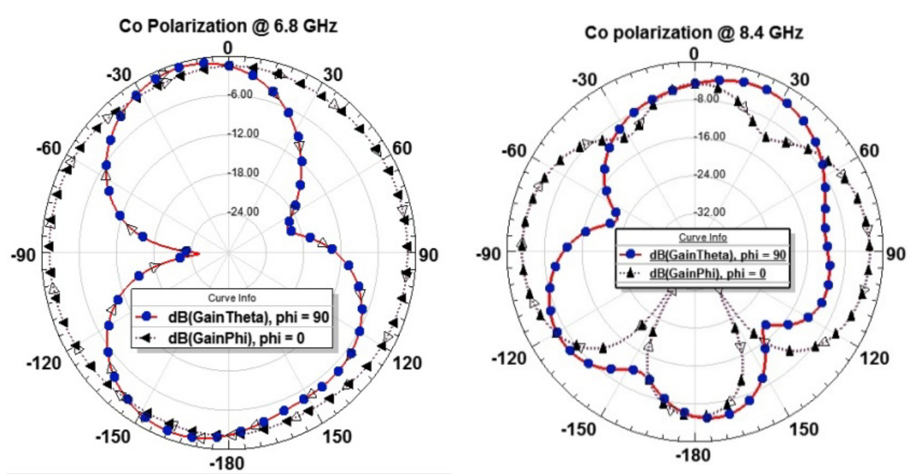


Figure 8. Simulated (solid line) and measured (dotted line) radiation plots at 6.8, 8.4, 10.6 and 11.8 GHz.



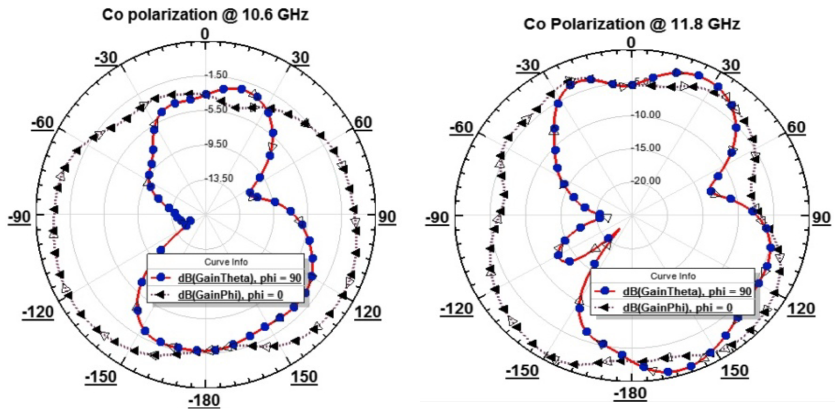


Figure 9. Co polarization at 6.8, 8.4, 10.6 and 11.8 GHz.

4.3. Antenna Gain and Efficiency

The variation in peak gain as a function of frequency is plotted in Figure 11. From the presented result, it is observed that the gain increases with frequency, and the maximum gain of 5 dB is achieved at 11.5 GHz. It can be seen that the gain of the antenna is less than 0 dB over 4–7 GHz. Therefore, the antenna is not suitable for operation in this frequency band. However, a good agreement between the simulated and measured results is noticed in the whole frequency band. The radiation efficiency of the antenna is depicted in Figure 12. It is apparent that the radiation efficiency around 88% is realized in

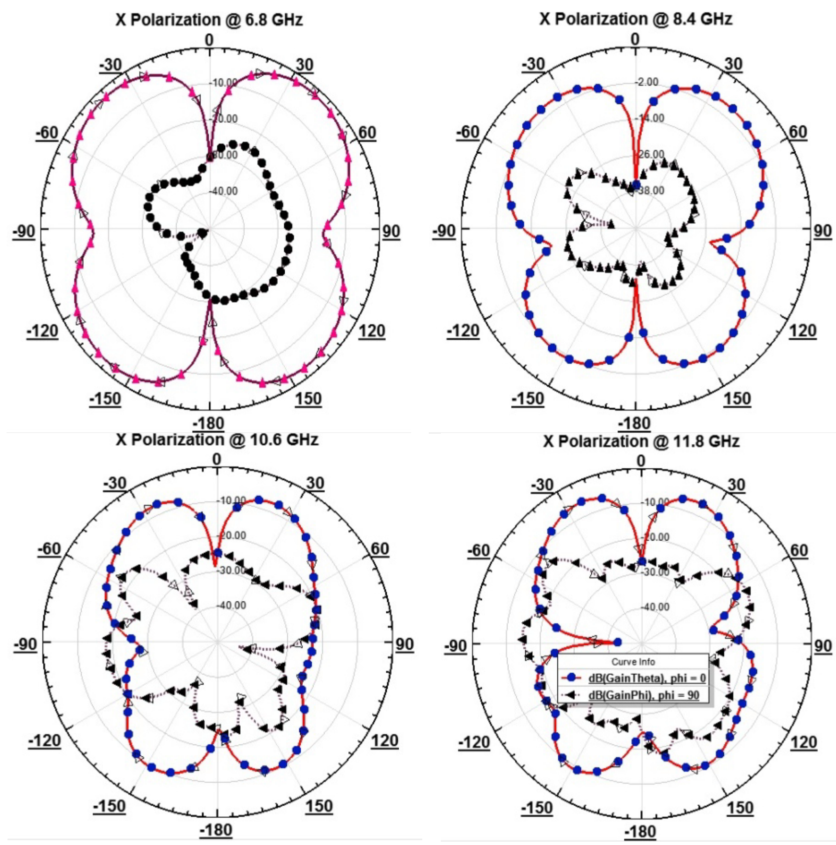


Figure 10. Cross polarization at 6.8, 8.4, 10.6 and 11.8 GHz.

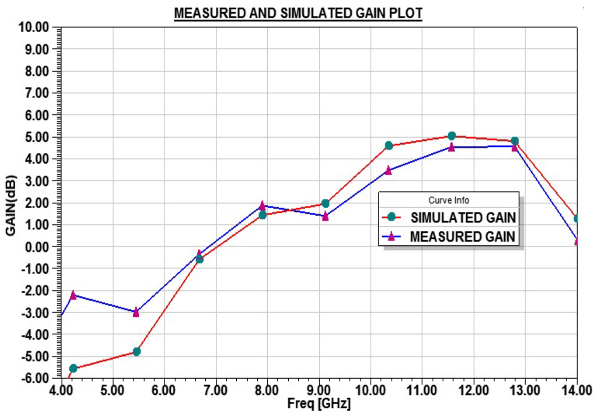


Figure 11. Simulated and measured gain.

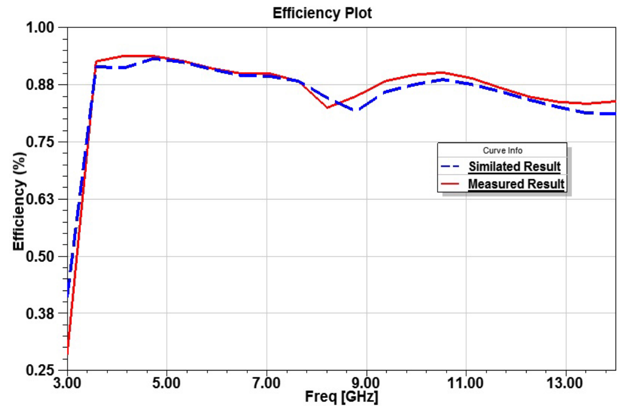


Figure 12. Comparison between simulated and measured efficiency.

the whole bandwidth. It is also seen that the measured and simulation results are in good agreement. Besides, the small deviations may be due to the limitations in fabrication and measurement setup.

A comparison of geometrical data and performance of the proposed antenna with those reported in the literature is given in Table 2.

Table 2. Comparison of the proposed antenna and antennas in literature.

Ref.	Size (mm^3)	Frequency (GHz)	Bandwidth (GHz)	Gain (dB)	Efficiency (%)
[10]	$170 \times 70 \times 6$	3.1–10.6	7.5	8.0	80
[11]	$56 \times 50 \times 0.8$	2–12	10	5.2	83
[14]	$25 \times 30 \times 0.8$	3–25.2	22.2	9.8	-
proposed	$32 \times 28 \times 1.6$	4.2–13.6	9.4	5.0	88

From Table 2, it is clear that the proposed structure is smaller in size than the antennas in [10, 11], and its dimension is comparable with the antenna in [14]. The antenna in [9] is a multiband antenna adopting hybrid fractal geometry, while the proposed antenna is a UWB linear fractal antenna. It is also established that the proposed antenna exhibits larger bandwidth and higher efficiency than the antenna in [10]. In addition, the size of the proposed antenna is reduced by 32% using the fractal geometry compared to the antenna in [10] which is only 23%. Furthermore, the antenna in [14] adopts a triangular slotted defective ground structure (DGS) for large impedance bandwidth, while the proposed structure is designed implementing square ring slots, and an appreciable bandwidth is achieved without DGS. Unlike the antenna in [11] which employs a complex feed network, the proposed antenna adopts a simple microstrip feed mechanism.

5. CONCLUSION

An ultra-wideband fractal antenna implementing circular radiating elements with square ring shaped slots has been reported. The proposed antenna shows remarkable performance with return loss below -10 dB in the broad operating band from 4.2 to 13.6 GHz. It is established that the circle radius, width of the circular ring, and fractal ratios significantly affect the antenna performance. The antenna parameters are optimized using full wave analysis to achieve ultra-wideband characteristics. The measured and simulation results show that the antenna exhibits an impedance bandwidth of 9.4 GHz with a maximum gain of 5 dB. It is revealed that the proposed antenna has low cross polarization and omnidirectional radiation characteristics. The physical size, impedance bandwidth, gain, and efficiency of the proposed antenna are compared with previously published reports. The performance of the proposed antenna is found better than that of others.

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