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A Miniaturized Decagonal Sierpinski UWB Fractal Antenna

Tanweer Ali*, Subhash B K, and Rajashekhar C. Biradar

Abstract—A miniaturized ultra-wideband (UWB) antenna based on Sierpinski square slots is reported. The antenna has a compact dimension of only $0.32\lambda_l \times 0.32\lambda_l$ ($28 \times 28\,\mathrm{mm}^2$), at a lower frequency of 3.4 GHz. Antenna miniaturization is achieved by etching Sierpinski square slots in the radiating decagonal shaped monopole, and UWB operations are accomplished by utilizing double truncations in the ground plane. The designed antenna has a fractional bandwidth of about 127.3% (3.41–15.37 GHz) in simulation and about 124.7% (3.50–15.1 GHz) in measurement. The time domain characteristics of the designed antenna are discussed in detail. Good radiation characteristics and impedance matching are exhibited by the designed fractal antenna in the entire UWB range.

1. INTRODUCTION

The recent years have witnessed a prompt growth in the wireless industry with tremendous-on-going research interest in the field of miniaturized UWB antennas. Higher spectral bandwidth and the necessity for high data rate based multimedia services with compact size pose major challenges on the conventional antennas [1–3]. With the allocation of UWB (3.1 to 10.6 GHz) by FCC, UWB communication systems have emerged as an alternative to narrowband systems, thus finding applications in indoor communications, wireless personal area network, remote sensing and radar imaging. UWB antennas provide high data rate communication in addition to low power consumption.

Antenna miniaturization can be achieved by the use of slots [4–6], fractals [7], metamaterials [8, 9], and Defected Ground Structure (DGS) [10, 11]. Ali and Biradar [12] proposed a miniaturized Volkswagen logo UWB antenna with a slot ground structure and circular Split Ring Resonator (SRR) for GPS, WLAN and WiMAX applications. Good gain and impedance bandwidth was obtained by employing an arc-shaped slot in a patch-based planar monopole antenna in [13]. Circular disc monopoles (CDM) were employed for achieving UWB operation in [14], due to non-dispersive and good radiation properties. Slots in conjunction with feeding techniques such as CPW feed are employed to achieve UWB operation, due to the ability to suppress multipath fading and improved quality of service in [15].

Of late, the space filling properties of fractals have been incorporated into the antenna to achieve miniaturization. The space filling property of the fractals enables efficient package of electrically large features into a small area [16, 17]. Since electrical lengths play a major role in antenna design, such an efficient packing technique can be used as a viable antenna miniaturization technique. Anguera et al. [18] proposed a Sierpinski based compact monopole for mobile communications. Ding et al. [19] exploited the self-similarity property of fractals to design a multi-frequency antenna structure with UWB properties. Similarly, fractalization of the patch achieved a miniaturization up to 31.2% in [20]. Ghanbari et al. [21] used fractal geometries to miniaturize a circular disk monopole antenna, achieving miniaturization of more than 50% while preserving the UWB property.

In this research, we present a new miniaturized fractal UWB antenna. The antenna consists of a Sierpinski square fractal slot in the radiating monopole to achieve miniaturization of about 46.3% and

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* Corresponding author: Tanweer Ali (tanweers@reva.edu.in).
The authors are with the Microwave and Antenna Research Laboratory, School of Electronics and Communication, REVA University, Bangalore 560064, India.

36% in active patch area and volume, as compared to a conventional decagonal antenna. The UWB operation in the proposed antenna is accomplished by creating double truncations at the ground plane. Parametric analyses are done to investigate the effect of various design parameters on the antenna performance. The time domain characteristics, such as group delay, isolation characteristics and phase response of the proposed design, are studied for both face-to-face and side-to-side conditions in detail.

2. DESIGN OF MINIATURIZED UWB ANTENNA

Obtaining antenna miniaturization using novel Sierpinski square fractal slot method and at the same time maintaining UWB operation with good time domain characteristics is the prime objective of this work. In order to attain this objective, the design evolution of the proposed structure is given in Figure 1.

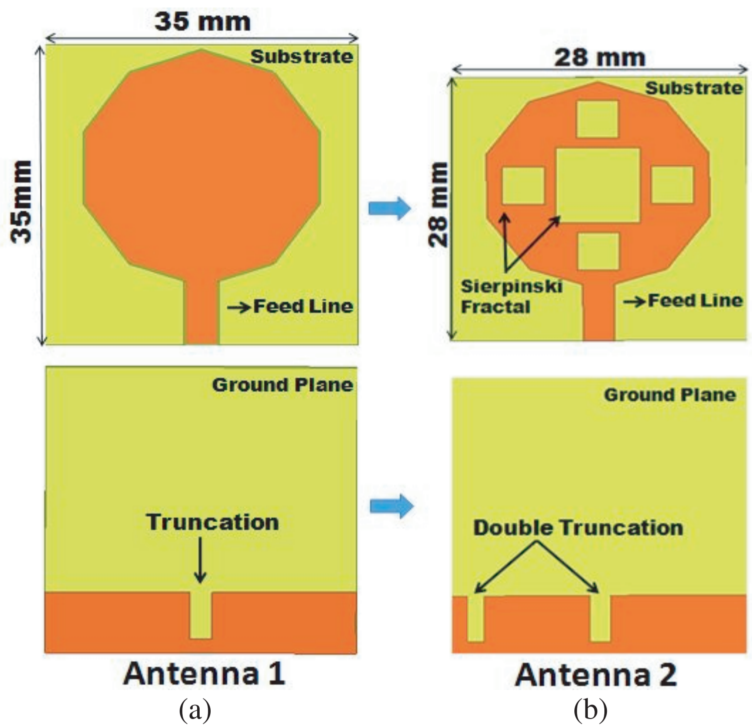


Figure 1. Miniaturization of the proposed UWB antenna, (a) Antenna 1, (b) Antenna 2.

Firstly, a conventional decagonal truncated UWB antenna of size $35 \times 35\,\text{mm}^2$ is designed. This antenna exhibits good UWB characteristics with $S_{11} < -10\,\text{dB}$ bandwidth ranging from 3.0 to 12.6 GHz (123.0%), as presented in Figure 2. To miniaturize this antenna, novel Sierpinski square slots are used, as illustrated in configuration "Antenna 2" of Figure 1. Fractal method is used in antenna miniaturization because it helps in achieving good miniaturization ratio, is compact in nature and provides easy integration with wireless handheld devices. Due to the introduction of this fractal slot, the surface current distribution of the monopole changes which affects the input impedance, thereby miniaturizing the antenna with respect to a given resonant frequency. The proposed decagonal is basically a monopole whose lower frequency can be calculated as $f_L = \frac{c}{4 \times L}$ where c is the speed of light in free space and is equal to $3 \times 10^8\,\text{m/sec}$, and L is the maximum length. The detailed analysis of this fractal patch is further discussed in Section 3. The aforementioned miniaturization process leads to about 46.3% and 36% miniaturizations in active patch area and volume of the proposed antenna, as compared to conventional decagonal UWB antenna (i.e., "Antenna 1"). The detailed miniaturization calculation is further given in Table 1. The UWB characteristics in the proposed antenna are accomplished by etching two truncations in the ground plane (Figure 1). As can be studied from Figure 2, this miniaturized

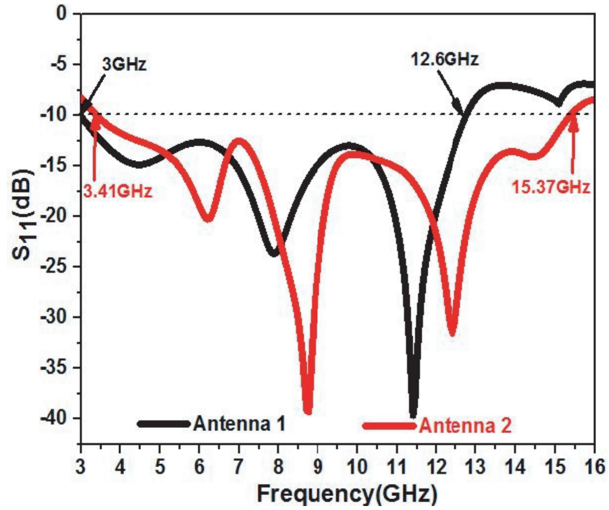


Figure 2. Reflection coefficients (S_{11}) for the two UWB configurations.

Table 1. Miniaturization calculation of the antenna.

Parameters	Operating band (GHz)	Volume (mm^3)	Patch area (mm^2)	Fractional Bandwidth	Miniaturization achieved in patch area (%)	Miniaturization in volume (%)
Antenna 1	3.00–12.6	1960	661.19	123.0%	-	-
Antenna 2	3.41–15.37	1254.4	354.73	127.3%	46.3%	36%

Sierpinski fractal antenna exhibits UWB characteristics with $S_{11} < -10\,\text{dB}$ bandwidth ranging from 3.41 to 15.37 GHz (127.3%).

The detailed layout of the proposed antenna is illustrated in Figure 3(a). It can be observed that the antenna consists of a decagonal Sierpinski square fractal slot (up to two iterations) as the radiating part and two etched out truncations as the ground plane. A microstrip feed line ($L_F \times W_F$) is included in the design to achieve good impedance matching across the entire UWB range. The different iteration stages of Sierpinski fractal square slot are illustrated in Figure 3(b). The optimized dimensions (mm) of the antenna are: $W = 28$, $L = 28$, $L_F = 5.96$, $W_F = 3$, $F = 8$, $H = 6.79$, $F1 = 4$, $T1 = 4.5$, $T2 = 4.5$, $S = 2$, $S2 = 1.5$, $S3 = 10$, $S4 = 13$, $S5 = 6$.

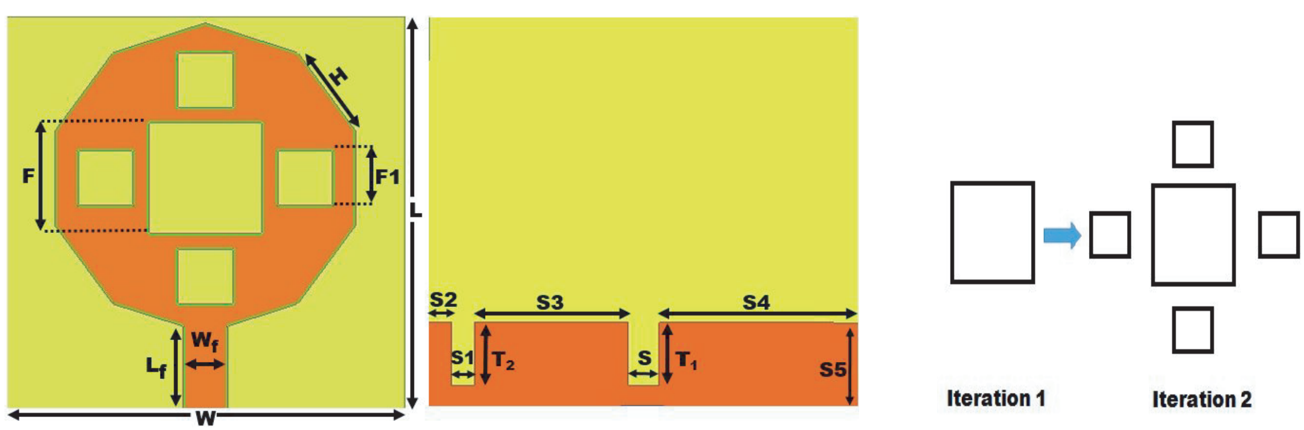


Figure 3. (a) Detailed dimension layout of proposed UWB antenna with fractal iterations, (b) iterations of Sierpinski square fractal slot.

3. DESIGN ANALYSIS OF THE PROPOSED FRACTAL UWB ANTENNA

3.1. Effect of Different Iterations of Sierpinski Fractal on UWB Characteristics

To analyze the effect of square fractal slot on the UWB characteristics, its analysis has been done and is depicted in Figure 4. The analysis is done till iteration 2 (Figure 4(a)), and its effect on S_{11} is illustrated in Figure 4(b). For iteration 0, S_{11} marginally shifts above -10 dB around 7 GHz. For iteration 1, better $S_{11} < -10$ dB bandwidth is achieved than iteration 0. For the proposed design, the best $S_{11} < -10$ dB bandwidth is achieved in iteration 2 (Figure 4(b)). Thus, it can be noticed that compared to iteration 0, iteration 2 helps in achieving better impedance matching over the entire UWB operation.

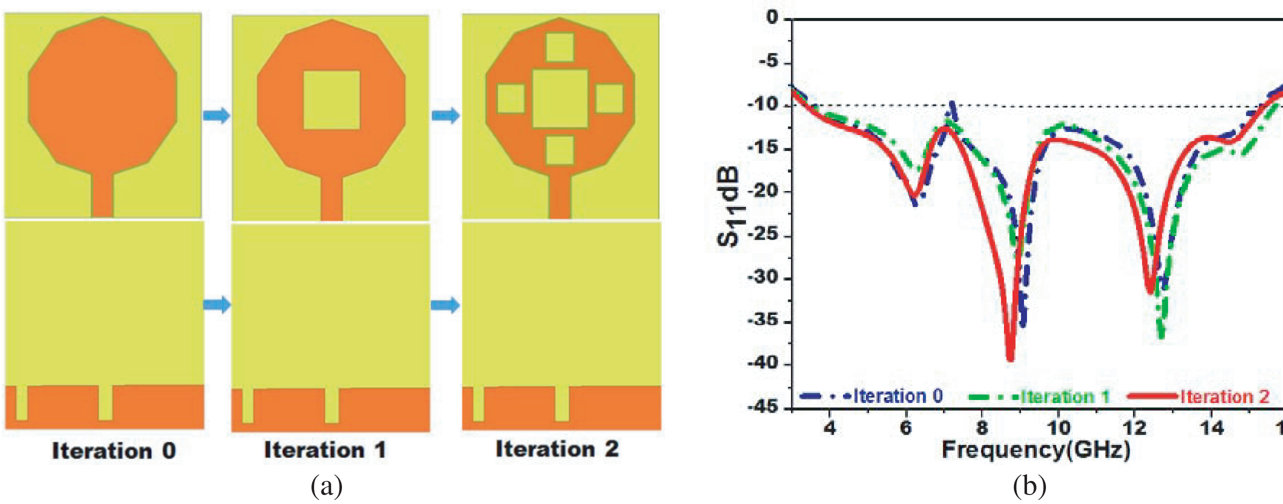


Figure 4. (a) Iterations of square fractal on the proposed UWB antenna, (b) S_{11} for the different iterations of square fractal slot.

3.2. Effect of Truncations on the Proposed Sierpinski Fractal UWB Antenna

Also, to study the effect of different truncations on the UWB characteristics of the proposed antenna, its analysis has been done and is depicted in Figure 5. From Figures 5(b) and (c), it can be seen that the antenna with double truncations ("Antenna B", i.e., proposed fractal UWB antenna) provides good UWB operation with acceptable impedance matching as compared to single and triple truncated antennas.

3.3. Parametric Analysis

In order analyze the effect of various parameters on the antenna operating performances, its parametric analysis is carried out. These analyses are done by varying one parameter at a time while keeping other parameters constant. The detailed analyses are as explained below,

3.3.1. Effect of Feed Width (W_F)

To achieve good impedance matching, the study of feed width is carried out. The study is done by varying W_F from 2.5 to 3.5 mm at a step of 0.5 mm, while keeping other design dimensions constant. From Figures 6(a) and (b), it can be seen that the best $S_{11} < -10$ dB bandwidth and impedance matching is exhibited for $W_F = 3$ mm.

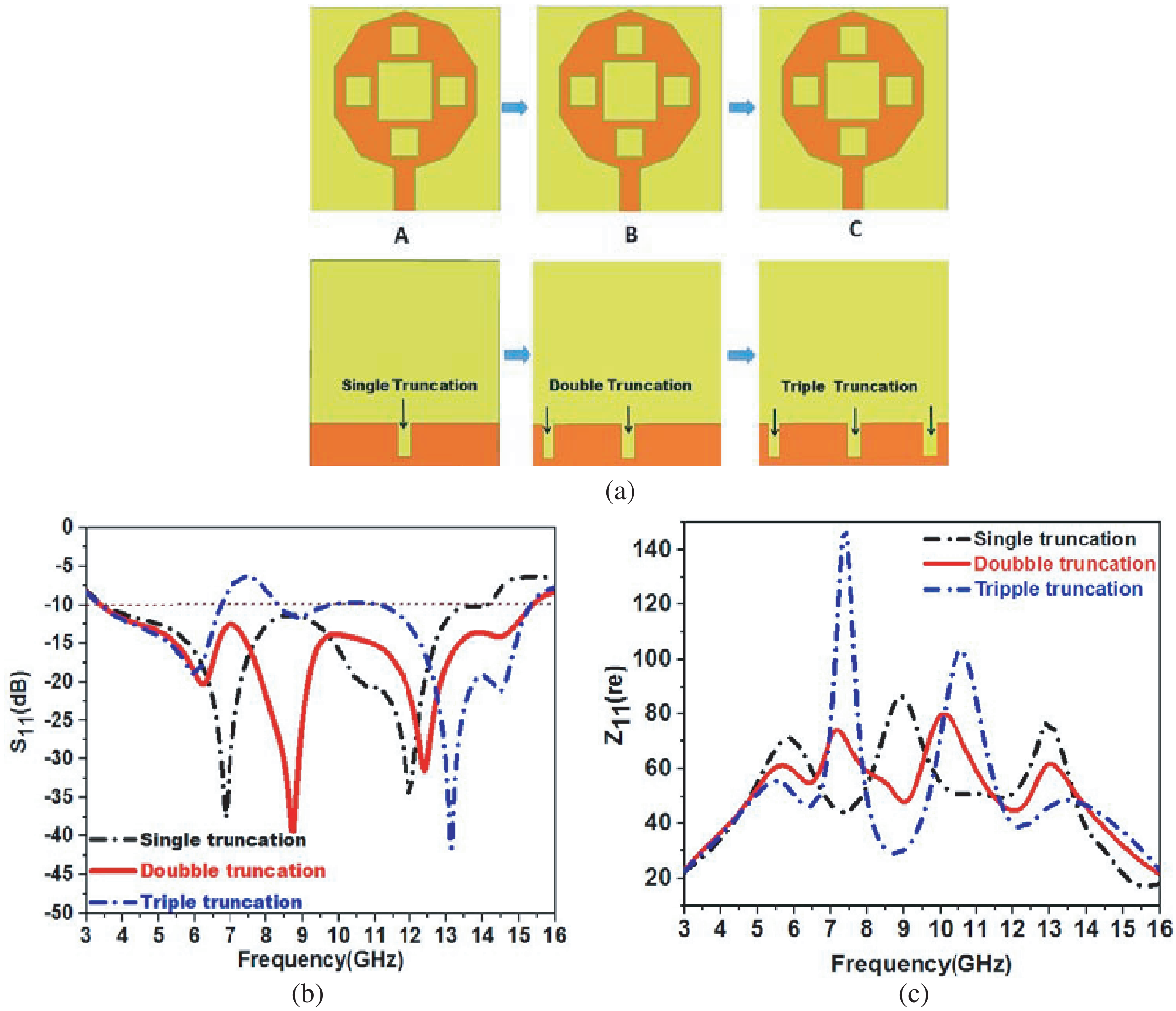


Figure 5. (a) Effect of different truncations on the proposed UWB antenna, (b) S_{11} for the different truncations and (c) impedance variation for different truncations.

3.3.2. Effect of Length of Truncation

(i) Effect of 1st Truncation Length (T_1)

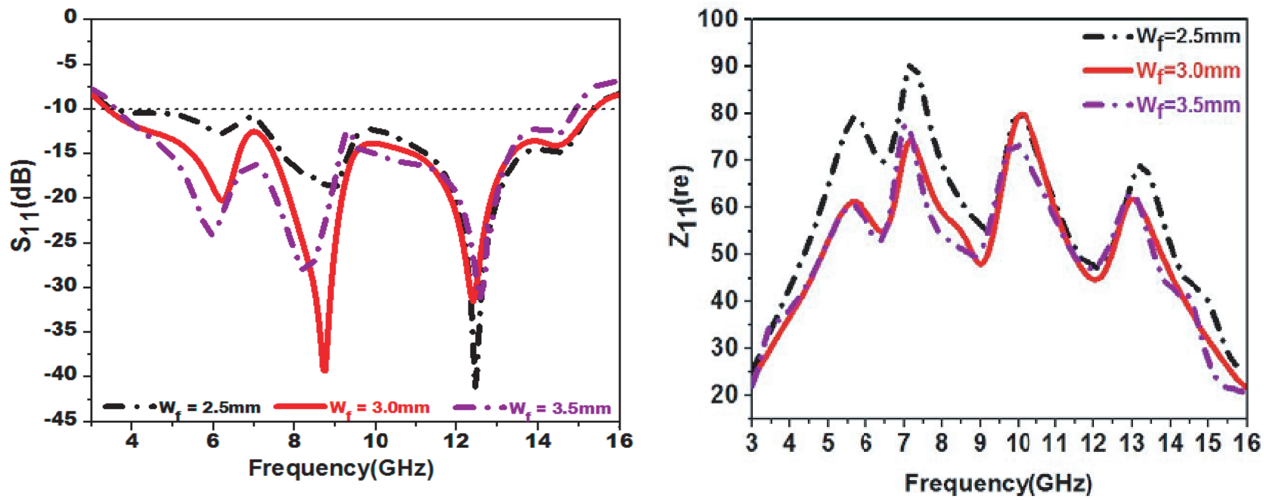
To investigate the effect of the first truncation length T_1 on antenna performance, analysis has been carried out by varying it at a step of 0.5 mm, from 4 to 5 mm. From Figure 7(a), at $T_1 = 4$ mm, the S_{11} curve lies close to -10 dB around 6.2 GHz. At $T_1 = 5$ mm the $S_{11} < -10$ dB bandwidth range is not good as $T_1 = 4.5$ mm. Also, from Figure 7(b) it is evident that the impedance matching is not proper at $T_1 = 4$ and 5 mm. Thus, the optimum performance with good UWB range is obtained for $T_1 = 4.5$ mm.

(ii) Effect of 2nd Truncation Length (T_2)

Similar to the analysis of truncation T_1, the best UWB characteristics and impedance matching are obtained for the 2nd truncation at $T_2 = 4.5$ mm, as illustrated in Figure 8.

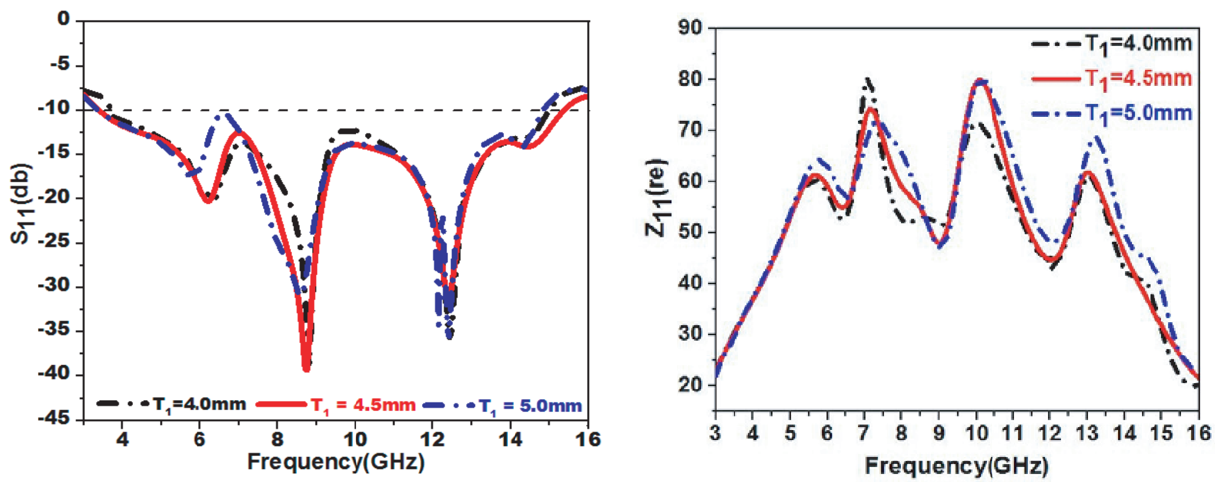
3.4. Current Distribution

In order to study the resonance behavior of the designed fractal UWB antenna, its surface current distribution is studied and depicted in Figure 9. The resonance characteristics are studied at the frequencies 6.2, 8.75, 12.5 and 14.5 GHz, respectively. As can be seen from Figure 9, for different operating modes, different parts of the antenna structure have a corresponding resonant path.



(a) (b)

Figure 6. Parametric study for W_F variation corresponding to (a) S_{11}, (b) real part of impedance (i.e., resistance).

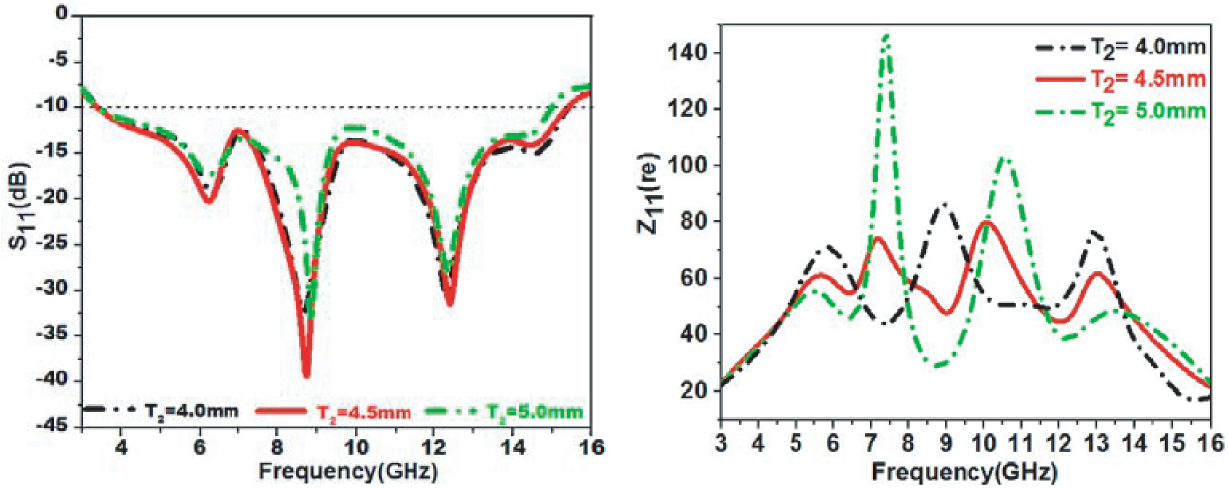


(a) (b)

Figure 7. Effect of 1st truncation length (T_1) on (a) S_{11}, (b) impedance.

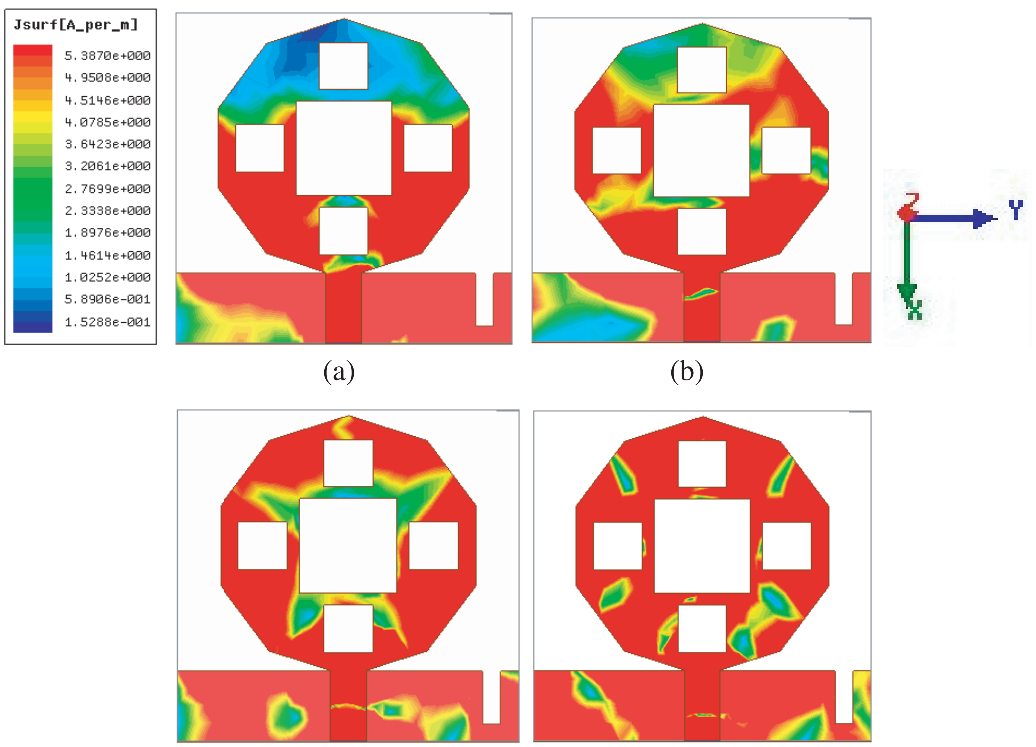
4. RESULTS

The proposed design illustrated in Figure 3 is simulated on HFSS v.13.0 using FEM method. The antenna is fabricated using photolithographic etching process on an FR4 substrate having $\varepsilon_r = 4.4$, $h = 1.6$ mm and $\delta 0.02$. The fabricated model of the proposed antenna is illustrated in Figure 10(a). The fabricated antenna S_{11} is measured using Rhode and Schwarz ZVL Network Analyzer. The experimental setup was calibrated carefully by considering the effect of feeding cable using an Agilent digital calibration kit. The compared simulated and measured S_{11} results are illustrated in Figure 10(b). The proposed design has $S_{11} < -10$ dB bandwidth of about 1196 MHz (3.41–15.37 GHz) in simulation and about 1160 MHz (3.50–15.1 GHz) in measurement, respectively. It is also evident from Figure 10(b) that the proposed design exhibits good UWB characteristics in both simulation and measurements. Slight glitches and more resonances in the measured results are observed which may be due to the fabrication of antenna during photolithographic process, soldering of SMA connector and manual tolerance. The simulated impedance characteristic of the proposed fractal UWB antenna is depicted in



(a) (b)

Figure 8. Effect of 2nd truncation length (T_2) on S_{11} and (b) impedance.



(a) (b)

(c) (d)

Figure 9. Surface current distribution of the fractal UWB antenna at (a) 6.2, (b) 8.75, (c) 12.5 and (d) 14.5 GHz.

Figure 11. From the figure it can be seen that the antenna has resistance near 50 ohms at the respective resonances in the entire UWB range.

4.1. Radiation Pattern

The simulated 3D polar gain plot of the proposed fractal UWB antenna at the resonance frequencies of 6.2, 8.75, 12.5 and 14.5 GHz is depicted in Figure 12. From Figure 12(a), it can be observed that

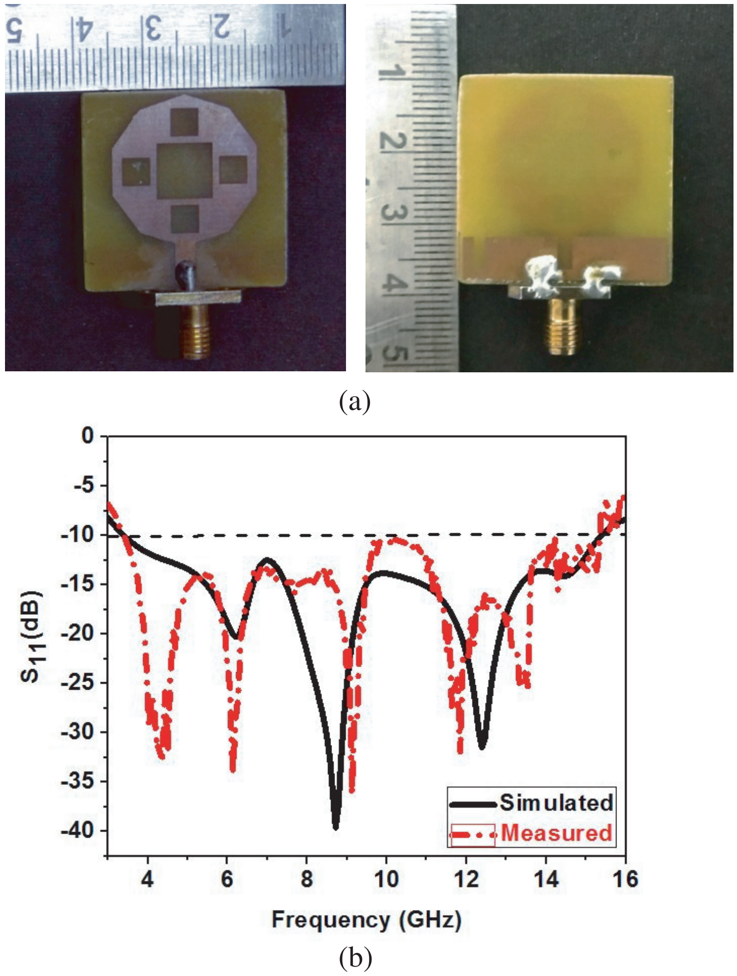


Figure 10. (a) Fabricated fractal UWB antenna front and back part and (b) compared simulated and measured S_{11}.

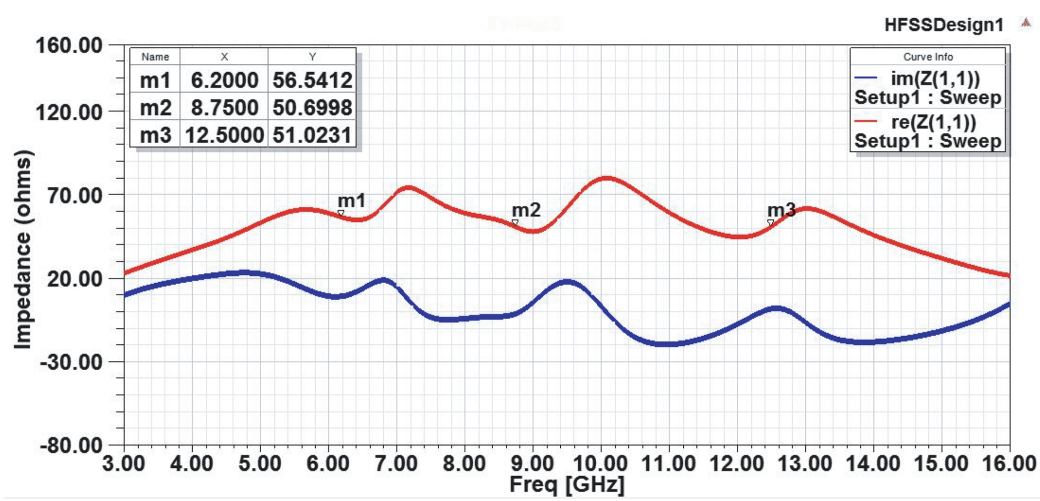


Figure 11. Impedance versus frequency characteristics of the proposed fractal UWB antenna.

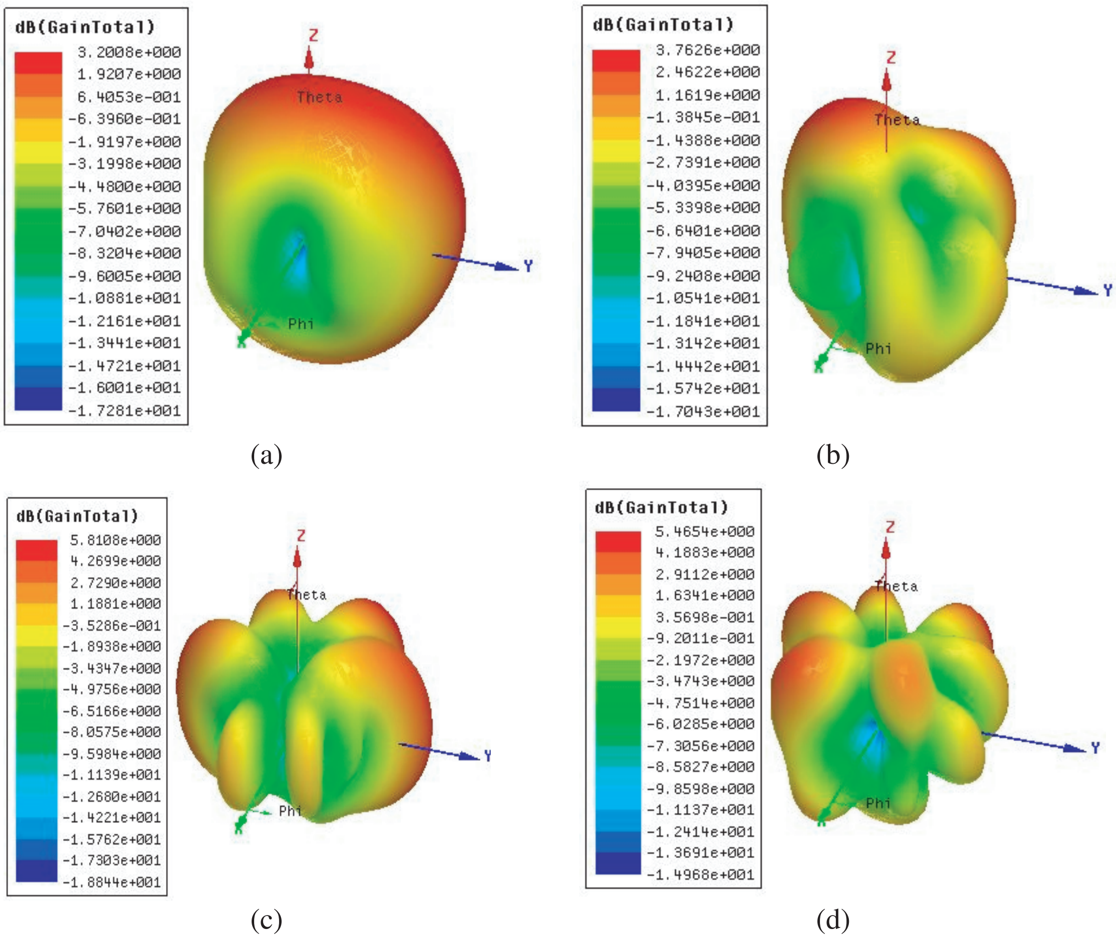


Figure 12. 3D polar gain plot at (a) 6.2, (b) 8.75, (c) 12.5 and (d) 14.5 GHz.

the pattern at 6.2 GHz is directional in nature with a total gain of 3.28 dB. At 8.75 GHz (Figure 12(b)), the pattern is bidirectional in nature with a small back lobe where a total gain of 3.76 dB is observed. Similarly for the resonance frequencies 12.5 and 14.5 GHz, a total simulated gain of about 5.81 and 5.45 dB is observed as depicted in Figures 12(b) and (c), respectively.

The radiation patterns of the proposed design at the resonance frequency are illustrated in Figure 13. The proposed fractal UWB antenna exhibits almost omnidirectional pattern in H-plane and bidirectional pattern in E plane at the frequencies < 6.2 GHz. For the frequencies > 6.2 GHz, the patterns tend to distort and acquire distorted omnidirectional pattern. These distortions can be attributed to the higher order modes excited at those frequencies.

4.2. Gain

The simulated and measured gains of the proposed fractal UWB antenna are illustrated in Figure 14. It can be observed that the antenna gain ranges from 1.7–5.95 dBi under simulation and from 1.4–5.72 dBi in measurement, for the entire UWB range of operation. The antenna has minimum gain of 1.7 dBi at 3.41 GHz and maximum gain of 5.95 dBi at 11 GHz in simulation. Under measurement the antenna has a minimum gain of 1.4 dBi at 6.5 GHz and maximum gain of 5.95 dBi at 11.5 GHz.

4.3. Time Domain Characteristics Analysis

To analyze the time domain performance of the proposed fractal UWB antenna, it is very much required to study the phase response, group delay and isolation characteristics, which seem as very important

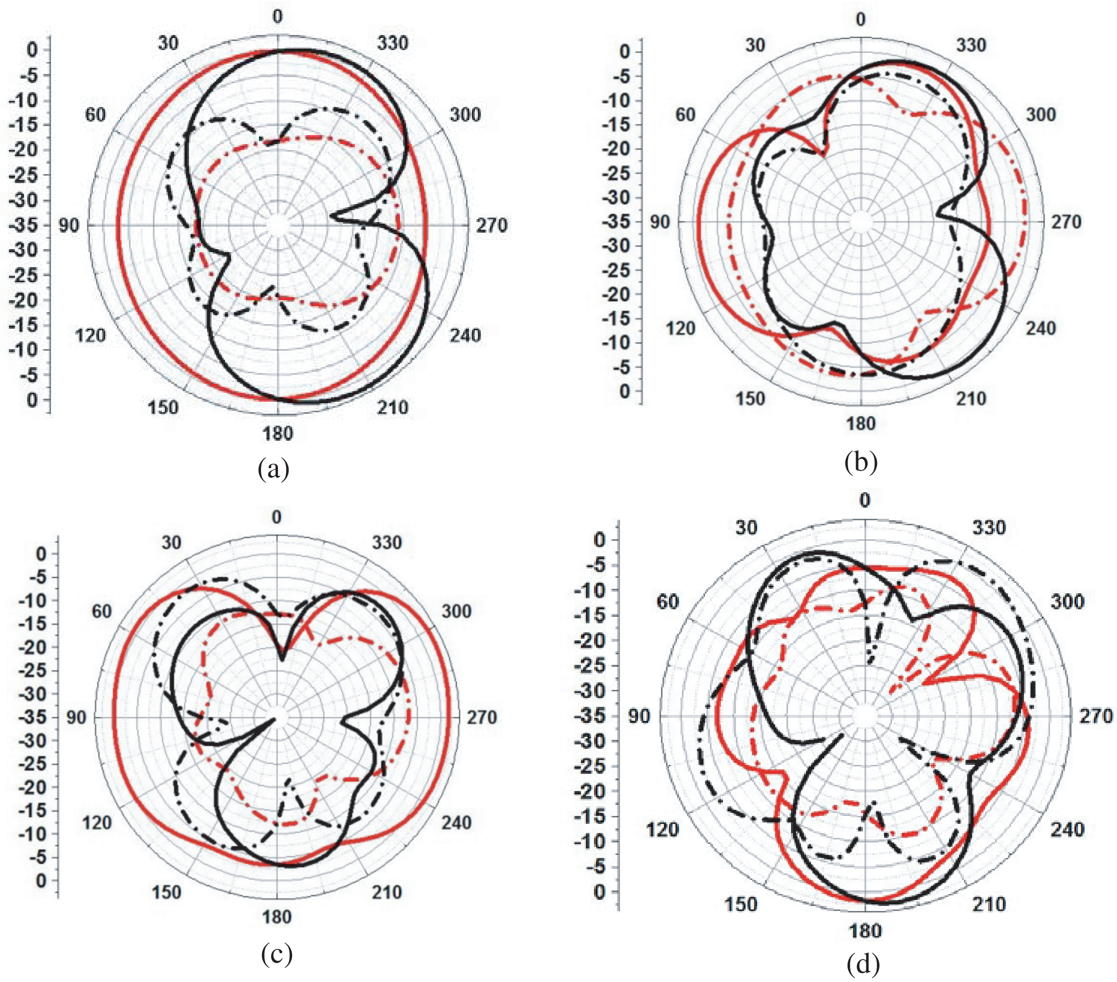


Figure 13. Radiation pattern of the proposed UWB structure at (a) 6.2, (b) 8.75, (c) 12.5 and (d) 14.5 GHz.

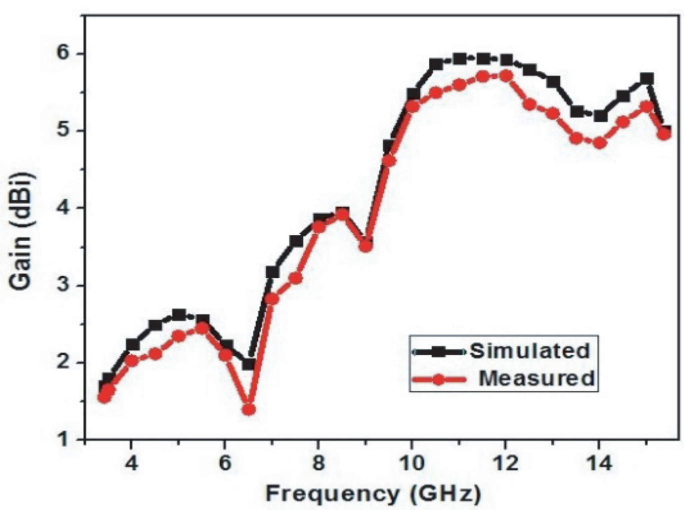


Figure 14. Gain (dBi) of the proposed design.

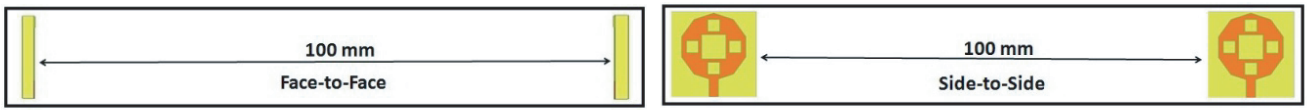


Figure 15. Orientations of proposed fractal UWB antenna in HFSS medium to calculate various time domain characteristics.

parameters for analyzing time domain characteristics. These time domain characteristics are measured for both Face-to-Face and Side-to-Side conditions by placing two identical antennas (i.e., proposed fractal antenna) at a distance of 100 mm in the HFSS environment as depicted in Figure 15.

4.3.1. Group Delay

The negative rate of change of transfer function phase with respect to frequency is called as group delay. The group delay of the proposed fractal UWB antenna is obtained from HFSS. Alternatively, it can be calculated as given in Equation (1) [23].

$$Group\ Delay = -\frac{\Delta\emptyset}{\Delta\omega} \tag{1}$$

where $\emptyset$ is the phase angle, and ω is the angular frequency. Basically, the group delay gives the measure of signal transition time through a device. For good time domain characteristics in the entire UWB operation, the group delay should be constant. From Figure 16, it can be observed that the group delay of the proposed configuration is almost constant (i.e., variation is < 2 ns) in the entire UWB range for both the conditions (i.e., Face-to-Face and Side-to-Side). Small variations in phase response and group delay are observed due to double truncations in the ground plane.

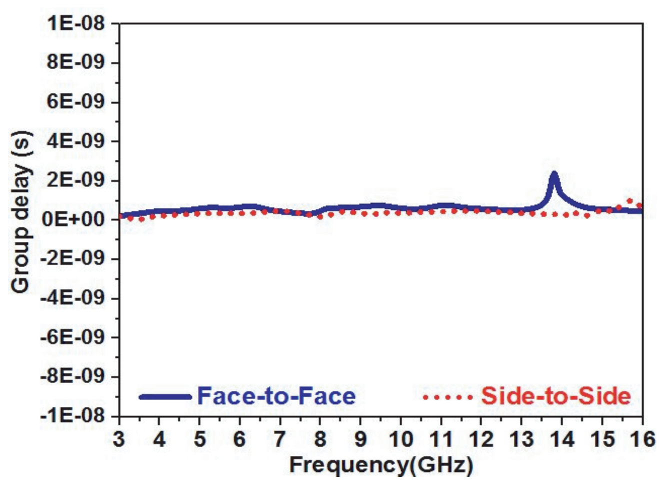


Figure 16. Group delay of the proposed fractal UWB structure.

4.3.2. Phase of S_{21}

Another requirement for good time domain characteristics in the entire UWB operation is that the phase response should vary in linear fashion. This is because the linear variation of phase indicates the absence of any out of phase component in the received signal. The phase of S_{21} versus frequency characteristics of the proposed fractal UWB antenna is depicted in Figure 17. From the figure it can be seen that the proposed configuration shows almost linear phase variation in the entire UWB operating range for both Face-to-Face and Side-to-Side conditions.

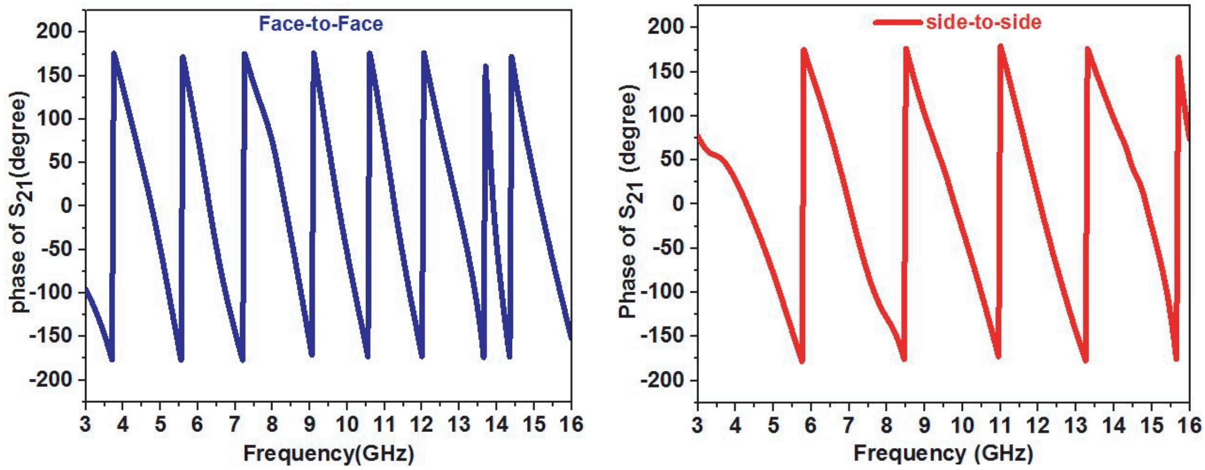


Figure 17. Phase response of the proposed fractal UWB structure. (a) Face-to-Face. (b) Side-to-Side.

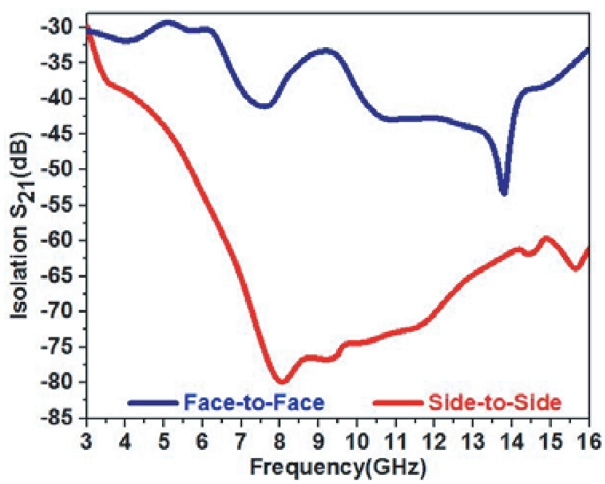


Figure 18. Isolation (S_{21}) Vs frequency characteristics.

Table 2. Comparison of the designed fractal UWB antenna.

Ref.	Dimensions (mm^2)	Operating range (GHz)	Miniaturization achieved in patch area (%)	Total Gain (dBi)
[20], 2016	43 × 40	2.5–14.38	31	3.7 at 6 GHz
[21], 2011	32 × 30	2.57–12.15	50	4.9 at 10.5 GHz
[22], 2014	31 × 28	3–12.8	-	6 at 12 GHz
[25], 2016	32 × 28	3.5–7.9	-	6.8 at 7.9 GHz
[26], 2017	35 × 35	2.8–12.2	23.4	-
[27], 2017	44 × 42	2.5–11.2	-	6.25 at 6 GHz
[28], 2016	35 × 24	3.1–12.3	-	4.2 at 4.5 GHz
[29], 2015	25 × 35	4.5 to 10	-	-
[30], 2014	30 × 30	3.85–16	-	-
This work	28 × 28	3.41–15.37	46.3	5.95 at 11 GHz

4.3.3. Isolation Characteristics

The isolation phenomenon of the proposed fractal UWB antenna for both the conditions is illustrated in Figure 18. A high value of isolation gives uncorrelated transmittance of electric signals at both the ports [24]. As can be seen from Figure 18, the proposed structure exhibits isolation (S_{21}) more than -28 dB for both the conditions in the entire UWB range.

Thus, from the aforementioned analysis it can be concluded that the proposed fractal UWB antenna exhibits good time domain characteristics in the entire bandwidth of operation.

To know the advantage of the designed fractal UWB antenna with those present in the state-of-art literature a comparative analysis is carried out and illustrated in Table 2.

5. CONCLUSION

A new miniaturized decagonal Sierpinski UWB fractal antenna is designed, simulated and then validated experimentally. It is seen that the Sierpinski fractal square slot helps in achieving antenna miniaturization of about 46.3% and 36% in active patch area and volume. The double truncations in the ground plane help in achieving UWB performance. The antenna has a good fractional bandwidth of about 127.3% (3.41–15.37 GHz) in simulation and about 124.7% (3.50–15.1 GHz) in measurement. The analysis of the optimized parameters/dimensions shows that slight change in their attributes affects the UWB operational characteristics. It is also seen that the reported antenna is new, compact, has good radiation characteristics, achieves good miniaturization and is more efficient than those reported in [20–22, 25–30]. Future work will focuse on achieving more miniaturization ratio by increasing the fractal iterations and at the same time achieving good radiation performances.

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