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Design and investigation of sectoral circular disc monopole fractal antenna and its backscattering

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ABSTRACT

This article presents the design of sectoral circular disc fractal antenna. The proposed antenna has been excited using CPW – feed. The measured result of this antenna offers the ultra wideband characteristics from 3.265 GHz to 15.0 GHz. The measured and simulated results are compared and found in good agreement. The impedance match of the antenna throughout the band is improved by incorporating the rectangular slots in the ground plane. The measured radiation patterns of this antenna are nearly omni-directional in H-plane and bidirectional in E-plane. The backscattering of antenna is also discussed and calculated for antenna mode and structural mode scattering. This type of antenna is useful for UWB system, microwave imaging and vehicular radar, precision positioning location.

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1. Introduction

With the tremendous advancement in wireless communication systems, there is an increasing demand for miniature, low-cost and easy-to-fabricate ultra wideband antennas. The ultra wideband (UWB) spectral range declared in February 2002 by the FCC is from 3.1 GHz to 10.6 GHz [1]. The UWB system has the advantages of transmitting high data rate with low power consumption. The UWB system requires an UWB antenna of small size. It is difficult to design an antenna of compact size with the characteristics of omni-directional radiation patterns, constant group delay and phase linearity. In the open literature, many researchers have reported UWB monopole antennas designed on both non-planar and planar structures. A non-planar UWB antenna has been reported in [2] while an UWB planar monopole antenna with direct probe feed reported in [3]. However, these antennas exhibit UWB characteristics with a bigger overall size and cannot be easily integrated with MIC/MMIC devices. Some researchers have reported UWB antennas with partial ground plane microstrip feed [4,5] and with coplanar waveguide (CPW) – feed [6,7]. The CPW-feed has many advantages in comparison with partial ground microstrip feed such as no double side printing, no alignment problem and low losses at higher frequencies. A CPW-feed is also advantageous for wide bandwidth and good radiation patterns and easily integrated with MIC/MMICs.

The miniaturization of antennas along with bandwidth enhancements are the two main challenges in UWB antenna design. Recently, fractal geometries have been reported as a promising research area in the design of UWB compact antennas and also advantageous for good impedance matching. Fractal geometries are characterized by self-similarity and space filling properties. These properties of fractal can be used in the design of various type of antennas and microwave circuits. Self-similarity offers the multiband properties or UWB feature of an antenna while spacing filling properties make the antenna/circuit miniaturized. The multi frequency properties of fractals when used as radiating structures were first reported in [8]. Fractals might also join some of the early designs based on self scaling properties however they are of bigger size [9]. Puente et al. first reported the behaviour of a fractal multiband antenna i.e. Sierpinski monopole [10]. Some steps further in the field of multiband fractal antennas were published in [11–13]. Fractal antennas with multiband properties have also been reported in [14]. The multiband resonances generated using the defected ground structure (DGS) and DGS effects on size reduction of antenna and Mutual coupling of arrays is reported in [15]. But multiband exhibits by DGS are narrow bandwidth and complex to adjust the bands into the useful applications. The bandwidth enhancement of antenna by employing the fractal geometry with gap coupling has also been shown [16]. The proposed antenna is coaxially feed and bandwidth has been enhanced by merging the multiple resonances but size of antenna

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is bigger than the reported monopole antenna. Present author [17] has reported monopole antenna to achieve the UWB and dual polarization by implementing slot in patch and ground plane. Some planar monopole fractal antennas using partial microstrip feed and CPW – feed for UWB bandwidth were reported in [18–21]. Currently, fractal geometry is also being combined with Metamaterial (MTM) and has become a hot topic in antenna and microwave circuits research. For instance, fractal perturbation in CSRRs results in a significant lower resonance [22,23], multiband behaviour [24], and broadband performance [25]. Others researchers also introduced the Hilbert curve in artificial magnetic materials [26], and some authors even exploited fractal concept for elevation of pass band performance in UWB filter [27].

In this paper, fractal geometry on circular disc sectoral monopole antenna has been exploited to achieve the ultra wide bandwidth. Antenna with fractal geometry is advantageous for good impedance matching and good RCS also. The RCS of UWB fractal antenna is necessary to study because antenna scattering is the main contribution to the total radar cross section (RCS) of low-observable platforms. The antenna scattering is related with its feed port, which affects the design of antenna with low RCS and good radiation characteristic simultaneously [28–30]. Therefore, scattering behaviour of antennas is important for defence applications. In fact, antenna scattering can be a source of electromagnetic compatibility problems and can cause interference with other systems on the same platform. Wide usages of fractal antennas make sense in the RCS study and its reduction for antenna designer. The RCS reduction of fractal antenna in narrow band has been reported in [31]. But RCS reduction of multiband or UWB fractal antenna has not been reported in the open literature.

This paper presents the design of UWB fractal monopole antenna followed by a discussion on its backscattering properties. The proposed fractal antenna is excited with CPW – feed and studied with respect to the various design parameters and their effect on its impedance bandwidth. The proposed antenna is also validated experimentally. This antenna is characterized in terms of impedance bandwidth, radiation patterns, group delay and backscattering.

2. Fractal geometry of the proposed antenna

The proposed antenna has been designed for UWB characteristics. The antenna is made using an iterative structure as shown in Fig. 1. In the zeroth iteration, a cylinder of radius 15 mm is taken with the angle 120°. In the first iteration, four equilateral triangles of side length 5 mm are inserted and subtracted from the zeroth iteration. This becomes the first iteration of the antenna. For the second iteration, four equilateral triangles with side length of 3.175 mm are inserted in the second iterative structure and subtracted. This is called the second iteration. For the third iteration, four equilateral triangles of side length 2.0161 mm are inserted and subtracted from the second iteration. This is called the third iteration. For the fourth iteration, again four equilateral triangles with side length of 1.28 mm are inserted and **s**ubtracted from the third iteration. This becomes the fourth iteration of antenna. For the fifth iteration, four equivalent triangles with side length of 0.81294 mm are inserted and subtracted from the fourth iteration. This becomes the fifth iteration of the antenna and the structure of the final proposed antenna. The same process can not be repeated to the infinite iteration because of fabrication constraints. Here, the final antenna structure is taken with five iterations. Four equilateral triangles are present in each iteration and each of them is placed with 30° difference. The first equilateral triangle is rotated by 30°, the second is rotated by 60°, the third is rotated by 90°, and the fourth is rotated by 120°. These equilateral triangles are inscribed into the cylinder in each iteration. The radii of the cylinders in various iterations are 15.0 mm, 10.654 mm, 7.44 mm, 5.258 mm, 3.753 mm, and 2.73 mm respectively in the decreasing order of the iteration. The central metal parts of the equilateral triangles are removed to form the fractal geometry.

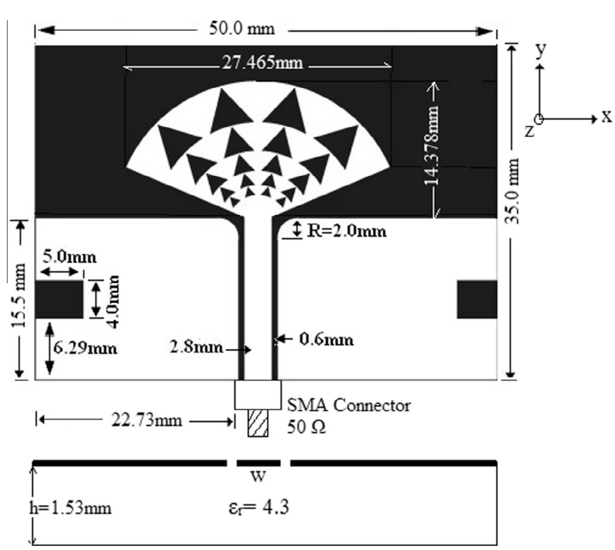

Fig. 1. Proposed fractal antenna with CPW – feed.

This final proposed antenna has been fed with CPW-feed as shown in Fig. 1 and it has been designed on a substrate of dielectric constant $\varepsilon_r = 4.3$ and thickness 1.53 mm. The size of the antenna structure is 32.5 mm × 37.46 mm. The width of the CPW-feed has been taken $W = 2.8$ mm and spacing between feed and ground is 0.6 mm. This makes the feed line's characteristic impedance $Z_0 = 50\ \Omega$. Thus, it can be connected with a 50 Ω SMA connector directly. The length and the width of the ground planes for the CPW – feed are optimized at 15.5 mm and 22.73 mm respectively. The overall dimension of the substrate is 35.0 mm × 50.0 mm. The proposed antenna is shown in Fig. 1 with optimized dimensions.

3. Simulated results

The proposed antenna has been simulated for each of the design parameters which affect the performance of the antenna. The gap between the patch and the ground plane, the gap between the ground and the feed line, the length and width of the ground plane, all are critical parameters which have an influence on the antenna bandwidth. This is because the current distribution is at the edges of the patch and along the upper edges of the ground plane as shown in Fig. 2. So, the gap between the patch and the ground plane is critical to achieve UWB characteristics. The length of the ground plane is also important for monopole antenna. It should be around quarter wavelength $\lambda/4$. To accommodate the effect of substrate and fractal geometry, the length of the ground has to be optimized. The ground width of the proposed antenna has also been optimized for optimum performance. The gap between the feed and the ground is optimized for proper input impedance matching throughout the band.

3.1. Effect of gap between the patch and ground plane

The proposed antenna has been simulated for various gap between the patch and the ground plane. The simulated results of gap from 0.1 mm to 0.5 mm with the step of 0.1 mm are shown in Fig. 3. It is observed from the simulated results that as the gap decreases from 0.5 mm to 0.3 mm, the impedance matching improves. But a good impedance matching throughout the band

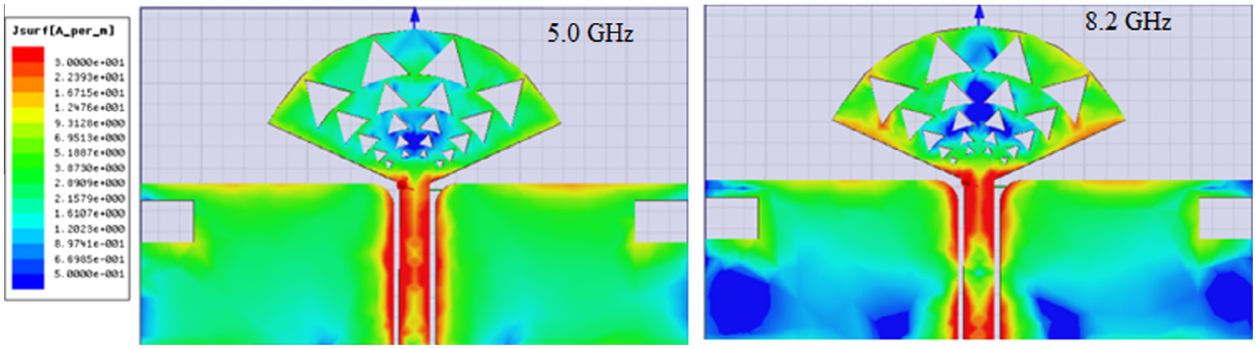

Fig. 2. Current distribution on the proposed fractal antenna.

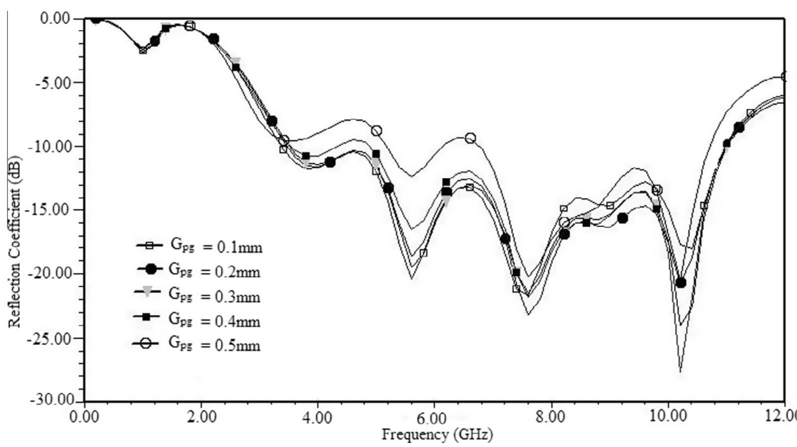

Fig. 3. Simulated results of proposed antenna for various gap between patch and ground plane (G_{pg}).

is achieved at the gap 0.3 mm. It is observed for gap 0.2 mm and 0.1 mm that the impedance matching deteriorates at higher frequency side.

3.2. The effect of the slot in ground plane

The effect of slot in the ground plane has been simulated. It is noticed from the simulated results that the return loss improves due to slot in the ground plane at higher frequency as shown in Fig. 4. The impedance matching improves at higher frequency by 5 dB. The size of the slot has been optimized to achieve the UWB characteristic. From the optimization, the width and length of the slot are fixed at 5.0 mm and 4.0 mm. The simulated results with the optimized slot and without the slot are compared as shown in Fig. 5.

3.3. Effect of the ground plane width (G_W)

In a CPW-feed, on both sides of the feed rectangular ground planes are placed. The width of the rectangular ground plane (G_W) is important because current distribution is along the *x*-axis of the ground plane as shown in Fig. 2 at 5 GHz and 8.2 GHz. The

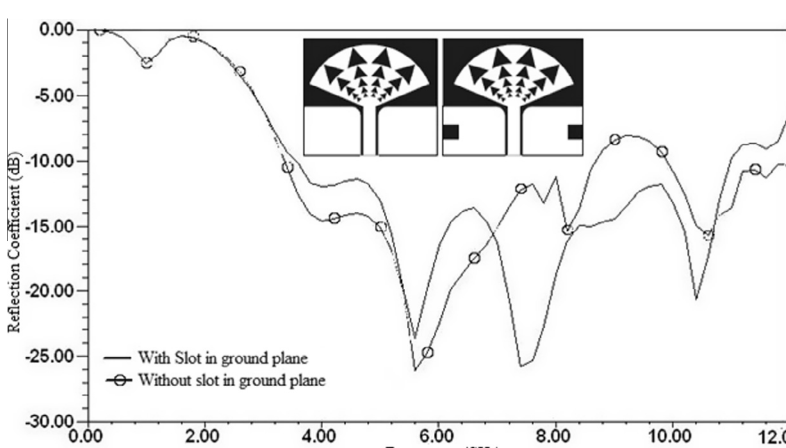

Fig. 4. Simulated results of proposed antenna with and without slots in ground plane.

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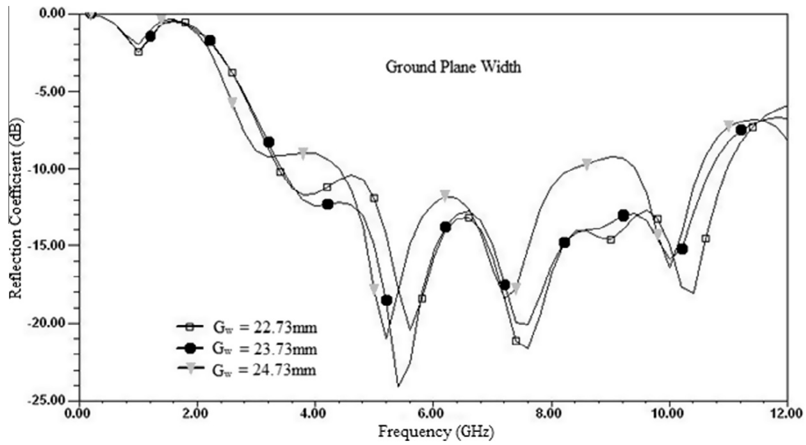

Fig. 5. Simulated results of proposed antenna with various values of ground plane width (G_w).

effect of the ground width has been simulated for various values of ground width. The simulated results for different ground plane widths are shown in Fig. 5 with the values varying from 22.73 mm to 24.73 mm with a step of 1.0 mm. Here, all other parameters are kept fixed (G_{pg} = 0.3 mm, G_L = 20.5 mm, G_{fg} = 0.6 mm and W = 2.8 mm). It is noticed that, as the ground width (G_W) increases from 22.73 mm to 24.73 mm, the lower end frequency shifts towards the lower side. There is an optimum value of width which offers the impedance bandwidth throughout the band. This is because the ground width behaves like an inductive resonant circuit over which the current is distributed along the *X*-axis. As the ground width increases or decreases, the inductive reactance also increases or decreases. But at the optimum ground width value, this inductive part is minimum. It means the ground width of a CPW-feed monopole antenna plays an importance role in achieving the ultra wide bandwidth of the antenna.

3.4. Effect of the ground plane length (G_L)

The effect of the ground plane length is also simulated using 3D electromagnetic simulator HFSS. The simulation has been carried out for the ground length (G_L) from 15.5 mm to 17.5 mm with a step of 1 mm keeping all other parameters fixed; G_w = 22.73 mm, G_{pg} = 0.3 mm, G_{fg} = 0.6 mm and W = 2.8 mm. The simulated results are shown in Fig. 6. It is observed from the simulated results, as the ground length increases the lower end frequency shifts slightly towards the lower frequency side. No major effect has been observed at higher frequency side in terms of bandwidth. It indicates that the ground length does not affect considerably the bandwidth of the antenna.

4. Experimental results and discussions

The proposed fractal antenna with the optimized dimension is shown in Fig. 1. The antenna has been fabricated with these optimized dimensions with and without the slot. The photograph of the proposed fractal antenna with and without the slot is shown in Fig. 7. The antenna has been tested using vector network analyzer R & S VNA ZVA40. The experimental result of the proposed antenna with the slot exhibits UWB characteristics from 3.265 GHz to 15 GHz. The antenna has been simulated using HFSS software based on the finite element method and CST MW Studio based on the finite integration method. The experimental and simulated results are in good agreement as shown in Fig. 8. This antenna is fed with CPW-feed and two rectangular slots in the ground planes have been incorporated to improve the return loss at higher frequency. This gives the 4–5 dB improvement in the return loss around 9 GHz. In the proposed fractal antenna, the fractal geometry is incorporated in the solid sectoral circular disc of radius 15 mm. It means the length of the monopole formed is 15 mm which gives the first resonance corresponding to $\lambda = l/4$ at around 5 GHz. A circular disc monopole of 15 mm diameter will also give the fundamental frequency at around 5 GHz. But the difference between the 15 mm diameter circular disc monopole and

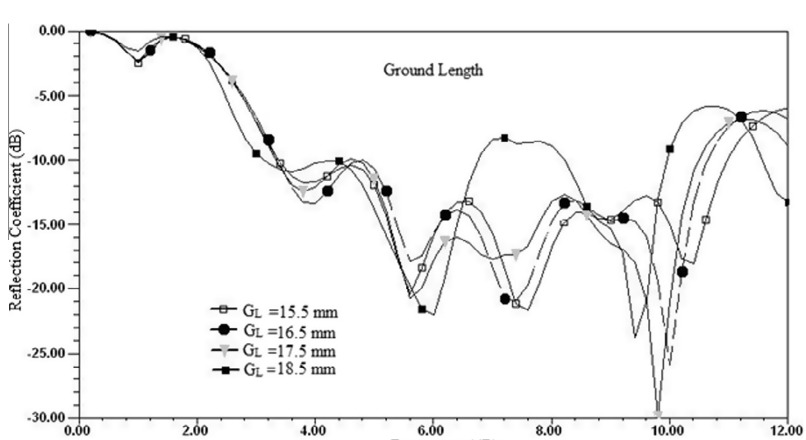

Fig. 6. Simulated results of the proposed antenna with various values of ground plane length.

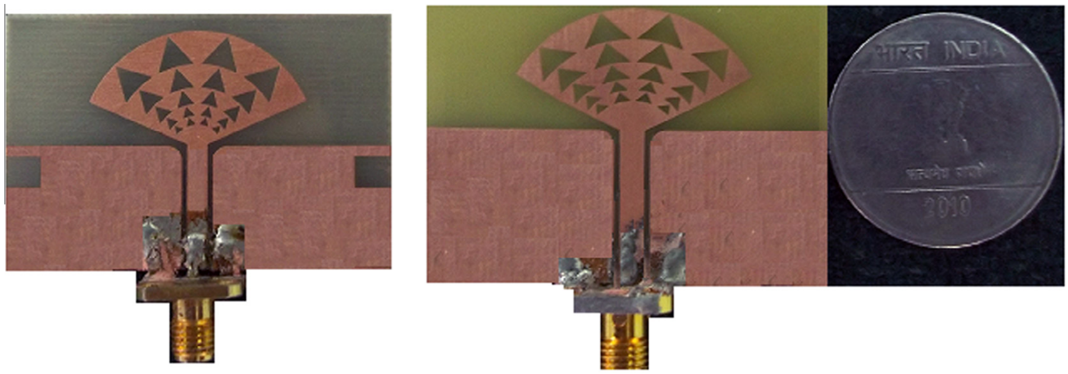

Fig. 7. (a) Photograph of proposed fractal antenna (b) photograph of fractal antenna without slot.

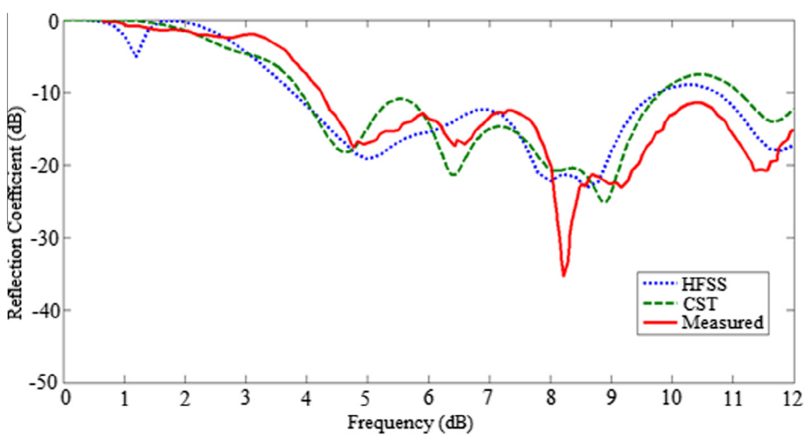

Fig. 8. Experimental and simulated results of proposed fractal antenna with slot.

the 15 mm sectoral circular disc monopole is better impedance matching achieved with the latter. The 15 mm sectoral disc monopole exhibits better impedance matching because of flaring with 120° angle. Incorporating the fractal geometry in the present structure further enhance the impedance matching. As shown in Fig. 8, this antenna resonates at multiple resonance frequencies (modes) i.e. 4.75 GHz, 6.42 GHz, 8.1 GHz, 9.1 GHz and 11.5 GHz. These measured resonance frequencies are almost in good agreement with the simulated multiple resonance frequencies from HFSS and CST software. These multiple resonance frequencies merge with each other and give the overall UWB bandwidth.

The fractal antenna without the slot and with ground width W_g = 24 mm and length G_L = 17 mm has also been tested. The measured and simulated results (from HFSS and CST software) are in good agreement as shown in Fig. 9. It is clear that without the slot and optimum ground width, the return loss is not below – 10 dB throughout the band. The measured and simulated results indicate the visible effect of slot as well as ground width.

The radiation patterns of the proposed fractal antenna have been measured at selective frequencies in an in-house anechoic chamber. The radiation patterns in the H-plane were measured at frequencies 4.7 GHz, 6.0 GHz, 8.0 GHz, 7.8 GHz, 9.8 GHz and

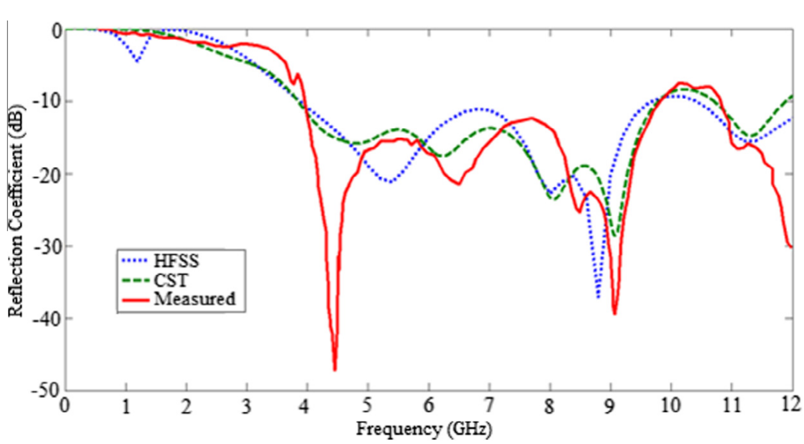

Fig. 9. Experimental and simulated results of fractal antenna without slot.

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12.0 GHz as shown in Fig. 10a. Similarly, radiation patterns in the E-plane were also measured at frequencies 4.7 GHz, 6.0 GHz, 8.0 GHz, 9.8 GHz and 12.0 GHz as shown in Fig. 10b. The radiation patterns in the H- and E-planes were also simulated using HFSS and CST Microwave Studio. The measured and simulated radiation patterns in both the planes are merged and compared. The measured and simulated radiation patterns are in close agreement. The nature of radiation patterns are nearly omni-directional in the H-plane and bidirectional in the E-plane. It is observed that as the frequency increases, the radiation patterns slightly vary. This may be because

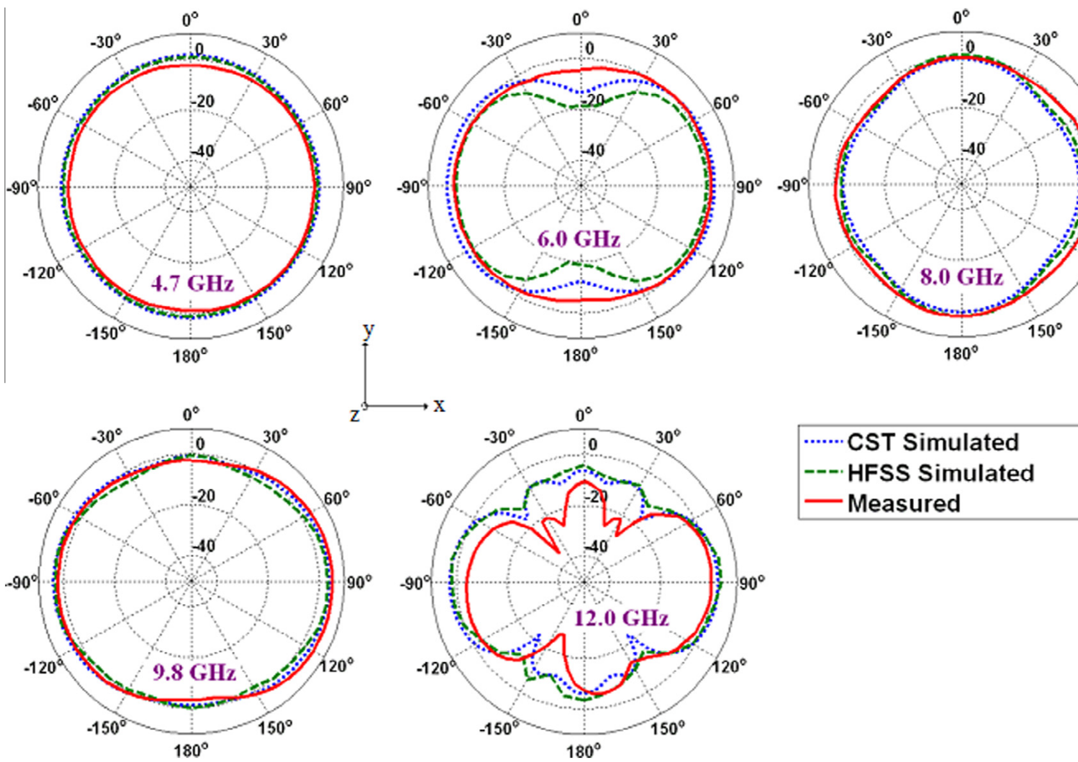

Fig. 10a. Measured and simulated H (XZ) – plane radiation patterns of proposed fractal antenna with slot.

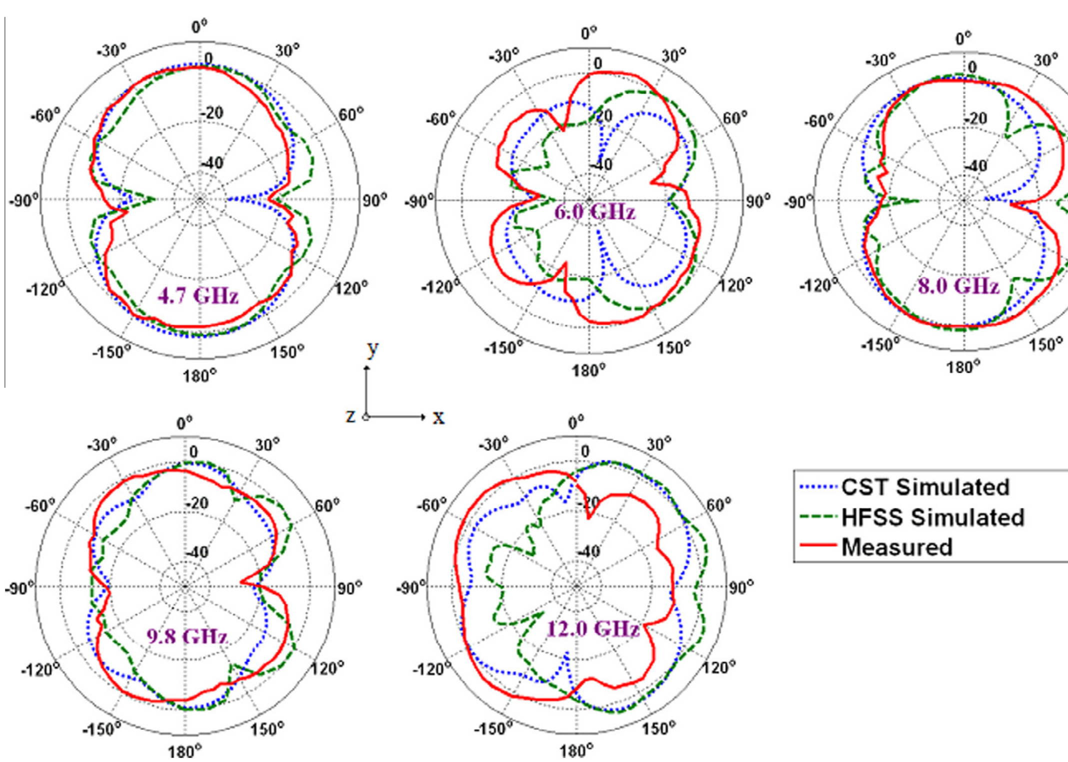

Fig. 10b. Measured and simulated E (YZ) – plane radiation patterns of proposed fractal antenna with slot antenna.

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of edge reflection, fractal nature of the antenna and lossy dielectric constant. The simulated HFSS and CST radiation patterns in the H- and E-planes also slightly vary. This difference in the radiation patterns is due to the fact that both the software are based on different numerical techniques. The radiation patterns in the E and H-plane for the antenna without the slot in the ground plane were also measured and simulated using both the software as shown in Fig. 11. A close agreement between the measured and simulated radiation patterns were also found for the antenna without slot. The radiation patterns of the antenna with slot are more stable than for the antenna without the slot throughout the band. The ripple in the radiation patterns are more in antenna without the slot. This is

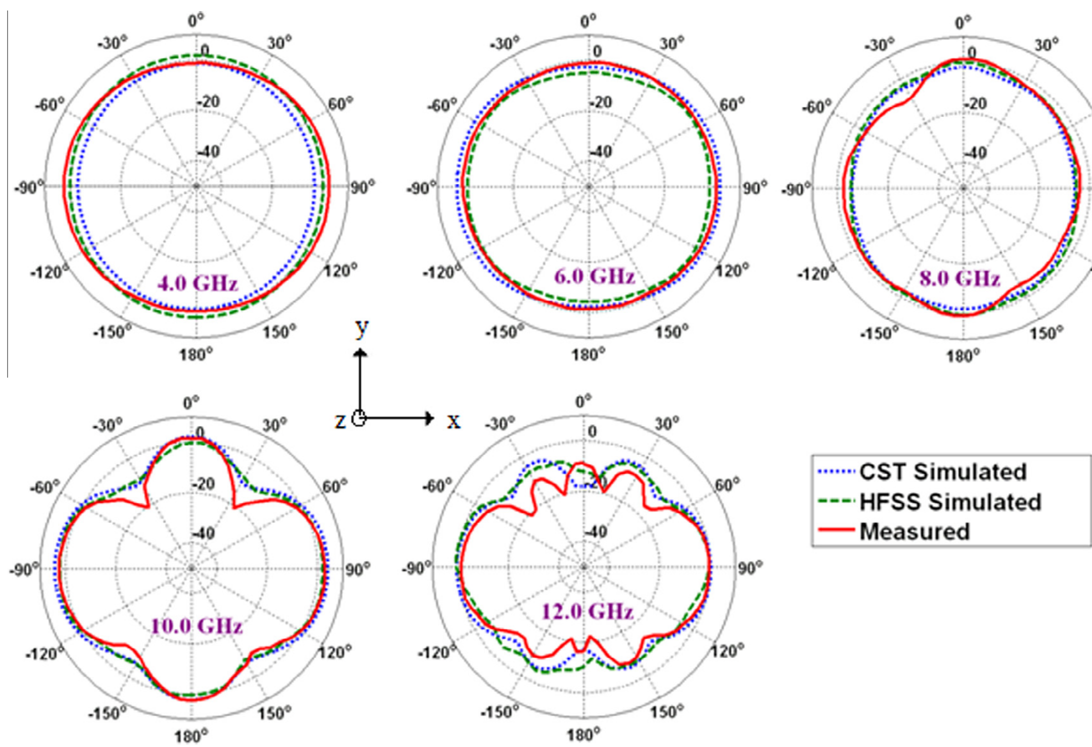

Fig. 11a. Measured and simulated H (XZ) – plane radiation patterns of fractal antenna without slot.

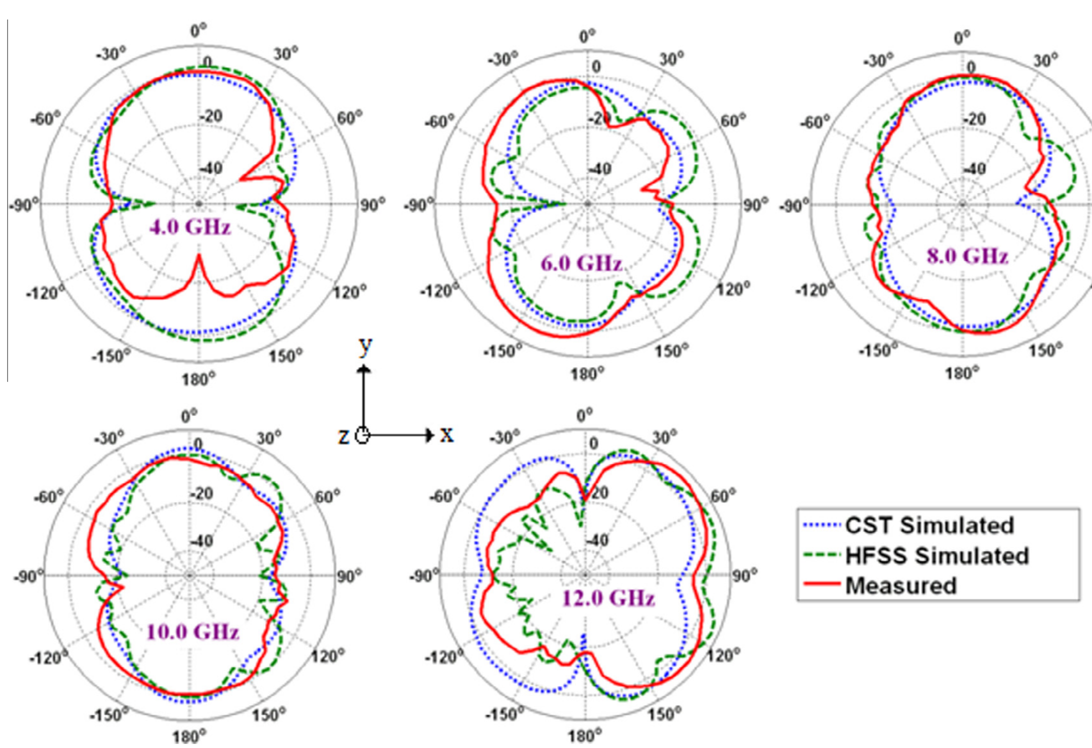

Fig. 11b. Measured and simulated E (YZ) – plane radiation patterns of fractal antenna without slot.

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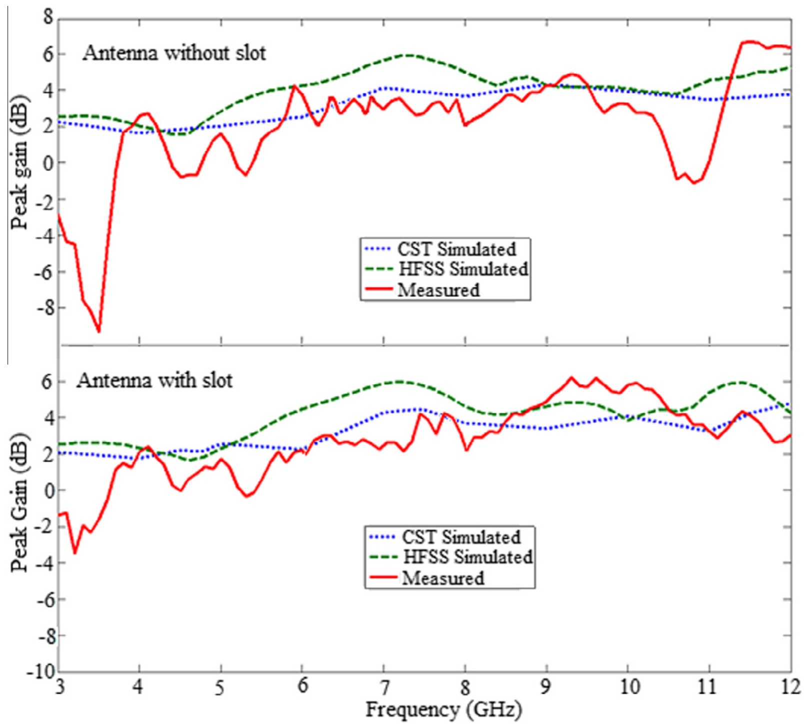

Fig. 12. Measured and simulated peak gain of fractal antenna with and without slot.

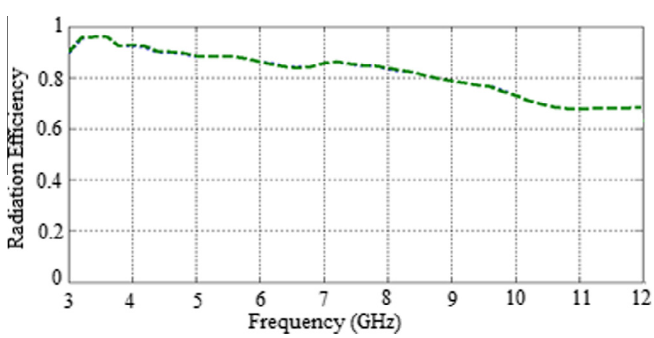

Fig. 13. Simulated radiation efficiency of proposed antenna.

because the return loss of the antenna without the slot is poor at higher frequency beyond 9.5 GHz.

The peak gain of the proposed fractal antenna with and without the slot in the ground plane is measured and simulated using both the HFSS and CST software. The measured peak gain with and without the slot are compared with the simulated peak gain as shown in Fig. 12. The peak gain of the proposed antenna increases as the frequency increases. This is because the effective area of the antenna increase as the wavelength becomes shorter at higher frequency. But beyond a certain higher frequency, it does not vary because of an increase in the loss of the substrate and cross polarization. The measured peak gain of the antenna without the slot decreases beyond the frequency 9.5 GHz. This is due to poor return loss at this frequency. The simulated radiation efficiency of the proposed antenna with slot is shown in Fig. 13. The efficiency is around more than 70% throughout the band. There is a reduction in the efficiency with an increase in the frequency which is due to an increase in the frequency dependent dielectric and copper losses.

5. Group delay and phase variation of the proposed antenna

One of the performance indicators for an ultra wideband antenna is the group delay which should be constant throughout the operating band to ensure minimum distortion in signal transmission. Mathematically, the group delay (τ) can be calculated by taking negative derivative of the transmission phase $\Phi(f)$ with respect to frequency f

$$\text{Group delay,} \quad \tau = -\frac{d\phi(f)}{2\pi df} \tag{1}$$

The group delay of the antenna is simulated by putting two identical antennas in far-field region. The simulated group delay of the antenna is shown in Fig. 14. It is seen that in the UWB region, the group delay variation is very small and almost constant throughout the band. This indicates UWB antenna system will have a very less distortion in received signal.

6. Backscattering results of proposed antenna

The RCS of an antenna is dependent on its feed termination. The monostatic RCS with open circuit, short circuit and matched – load (50 Ω) terminations are simulated in graphical as well as tabulated form using HFSS software. These simulated results of RCS with open circuit, short circuit and matched load terminations are used to calculate the RCS of structural mode scattering and antenna mode scattering using Eqs. (2) and (3) respectively [30].

The structural mode scattering (σ_s) is calculated using

$$\sigma_s = \left|\frac{(\sqrt{\sigma_0} + \sqrt{\sigma_{sh}})}{2}\right|^2 \tag{2}$$

where, σ_0 and σ_{sh} are the RCS with the open and short circuit termination. The antenna mode scattering (σ_a) is calculated using

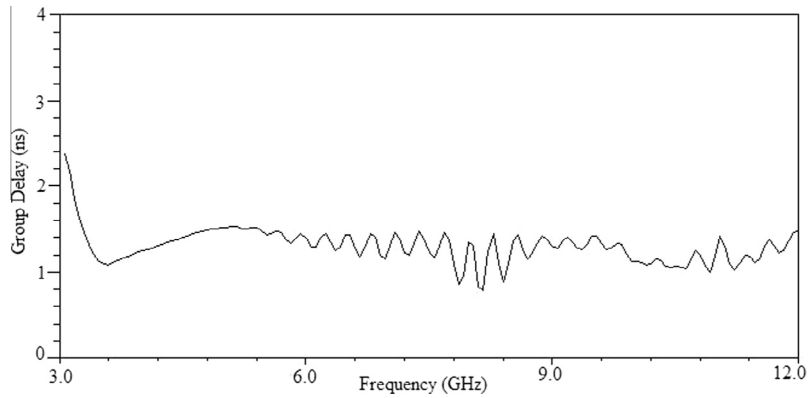

Fig. 14. Simulated group delay of proposed fractal antenna.

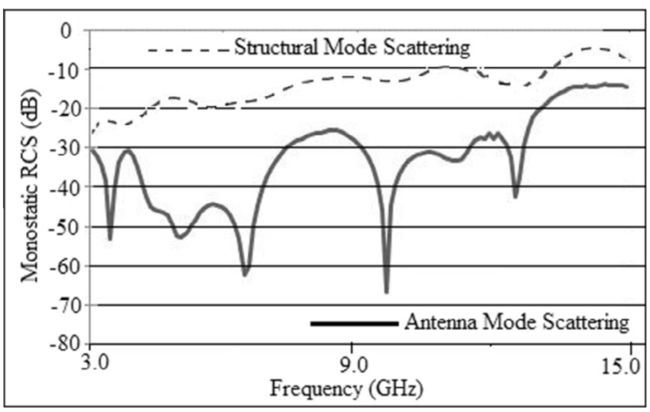

Fig. 15. Simulated monostatic RCS for antenna mode scattering of proposed fractal antenna.

$$\sigma_a = \left| \frac{\sqrt{\sigma_0} - \sqrt{\sigma_{sh}}}{2} \right|^2 \quad (3)$$

It is observed from the simulated results that the RCS of structural mode scattering of the proposed antenna is largely reduced at the high frequency range, which is due to the relatively small wavelength in comparison to the geometrical size of the antenna. In the low frequency range, RCS is large because the scale of the proposed fractal antenna is similar to the incident wavelength. Here, all the monostatic RCS are calculated for vertical polarization, i.e., both the incident and received electric fields are oriented along $\theta = 0$ and $\Phi = 0$.

The antenna mode and structural mode RCS of the proposed fractal antenna versus frequency is shown in Fig. 15. The proposed fractal antenna RCS throughout the band is around −28 dB with impedance matching throughout the band. The RCS of structural scattering mode is same as the RCS with matched termination. This indicates the potential of the proposed fractal antenna structure to be used for military applications for transmitting/receiving the high data rate secure wireless communications.

7. Conclusions

The UWB fractal antenna with slot in the ground plane has been successfully designed and experimentally implemented. The antenna exhibits the UWB characteristics from 3.265 GHz to 15 GHz corresponding to an impedance bandwidth of 128.497%. The experimental and simulated results are in good agreement. The measured radiation patterns of the antenna are omnidirectional in H-plane and bidirectional in E-plane. The group delay of the antenna has a negligible variation in the operating band. The monostatic RCS of the antenna is also studied for both the antenna scattering mode and the structural scattering mode. The RCS of the fractal antenna is good in the operating band. This makes this antenna a potential candidate for military applications. The proposed antenna is compact, simple to design and easy to fabricate and integrate with MMIC devices. The antenna is useful for UWB systems, medical imaging and vehicular radar for civil as well as defense applications.

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