

A CIRCULAR FRACTAL UWB ANTENNA BASED ON DESCARTES CIRCLE THEOREM WITH BAND REJECTION CAPABILITY

Rowdra Ghatak^{1, *}, Balaka Biswas², Anirban Karmakar³, and Dipak R. Poddar²

¹Microwave and Antenna Research Laboratory, ECE Department, National Institute of Technology Durgapur, West Bengal, India

²ETCE Department, Jadavpur University, Jadavpur, Kolkata, West Bengal, India

³ECE Department, Netaji Subhash Engineering College, Kolkata, West Bengal, India

Abstract—A novel planar circular Apollonian fractal shaped UWB monopole antenna with band rejection capability is presented in this paper. The antenna performs satisfactorily in the frequency range 1.8–10.6 GHz which gives a wide impedance bandwidth of 142% for VSWR within 2. The proposed antenna has the capability to reject the frequency band 5.125–5.825 GHz assigned for IEEE802.11a and HIPERLAN/2. This is achieved by a pair of narrow band resonant L-shaped slots in the CPW ground plane. The antenna exhibits satisfactory omnidirectional radiation characteristics throughout its operating band. The measured peak gain varies from 2 dBi to 6 dBi in the entire UWB band except the notch band. The performances of time domain characteristic is satisfactory with a group delay variation of 1 ns that shows the antenna is non dispersive. To ensure the usefulness of the proposed antenna in pulse communications systems, the correlation between the time-domain transmitting antenna input signal and the receiving antenna output signal is calculated. This antenna can be effectively used for medical imaging and military radar system along with other common UWB applications.

Received 16 January 2012, Accepted 25 February 2013, Scheduled 26 February 2013

* Corresponding author: Rowdra Ghatak (rowdraghatak@yahoo.com).

1. INTRODUCTION

February 2002 witnessed the allocation of the frequency band between 3.1 GHz to 10.6 GHz as the ultra wide band (UWB) application by Federal Communication Commission (FCC), USA [1, 2]. Since then, the research in the area of ultra wideband (UWB) systems has generated a lot of interest among microwave engineers. However, there are some narrowband systems, which co-exist with the UWB frequency range and interfere with UWB. Most notable among them there are IEEE802.11a and HIPERLAN/2 locating in the frequency range 5.125 GHz–5.825 GHz. So there is a need of filtering this band in order to avoid potential interference with UWB systems. To reject this frequency band, the easiest method is to use band stop filters [3–5] but this method not only increases the circuit dimension but also increases circuit complexity. So various techniques [6, 7] have been proposed till date to reject the unwanted sub bands in UWB domain. Among them, most notable examples are as inserting a T-shaped stub in the radiation patch [8, 9], a pair of parasitic strips beside the feed line [10] or by embedding sub wavelength structure like split ring resonators [11], inserting $\lambda/2$ and $\lambda/4$ resonators [12] or H-shaped slot cut away from radiating patch [13]. Alternative way is to use an arc-shaped parasitic strip besides the patch [14–16] or inserting notches in the feed line [17, 18]. A novel approach to obtain multiband miniaturized antenna was to include fractal geometry [19, 20]. The application of fractal geometry in printed monopoles provide for good radiation patterns and ultra wide bandwidth feature due to self similar and space filling property which in turn increases effective electrical length to reduce the size of the antenna and as a consequence, multiples resonances have been converted into wide band characteristics by bringing the resonances closer together. In this work, a novel circular shaped Apollonian fractal UWB antenna is constructed based on Descartes Circle Theorem (DCT) [21]. However, some other variants of DCT based fractal shaped antenna are reported in [22, 23]. The band notch characteristics are achieved by etching out a pair of L-shaped slots near the feeding point of the ground plane. Rest of the paper is divided as follows. Section 2 describes antenna design and parametric study and Section 3 includes results and discussion. This is followed by time domain antenna analysis and conclusion in Sections 4 and 5, respectively.

2. ANTENNA DESIGN AND PARAMETRIC STUDY

The geometry of proposed antenna is shown in Fig. 1(a). It is realized on FR4 substrate with relative permittivity 4.4, height of (h) 1.59 mm and having loss tangent ($\tan \delta$) of 0.02. The initial dimension of the proposed circular shaped Apollonian fractal shaped antenna is determined by $\lambda_g/4$ of lowest resonant frequency 2 GHz where λ_g is the guided wavelength. Thereafter fractal miniaturization technique lower band edge frequency to 1.8 GHz. The circular radiator is constructed with fractal patterns which satisfy the DCT [21]. It states that if four circles are mutually tangential in the plane, with disjoint interiors, then their curvatures satisfies the following relationship;

$$(a_i + b_i + c_i + d_i)^2 = 2(a_i^2 + b_i^2 + c_i^2 + d_i^2) \quad (1)$$

$i = 1, 2, \dots$, where $a_i = 1/r_{ai}$, $b_i = 1/r_{bi}$, $c_i = 1/r_{ci}$, $d_i = 1/r_{di}$ and radii of the circles shown Fig. 1 are r_{ai} , r_{bi} , r_{ci} , r_{di} . Initially

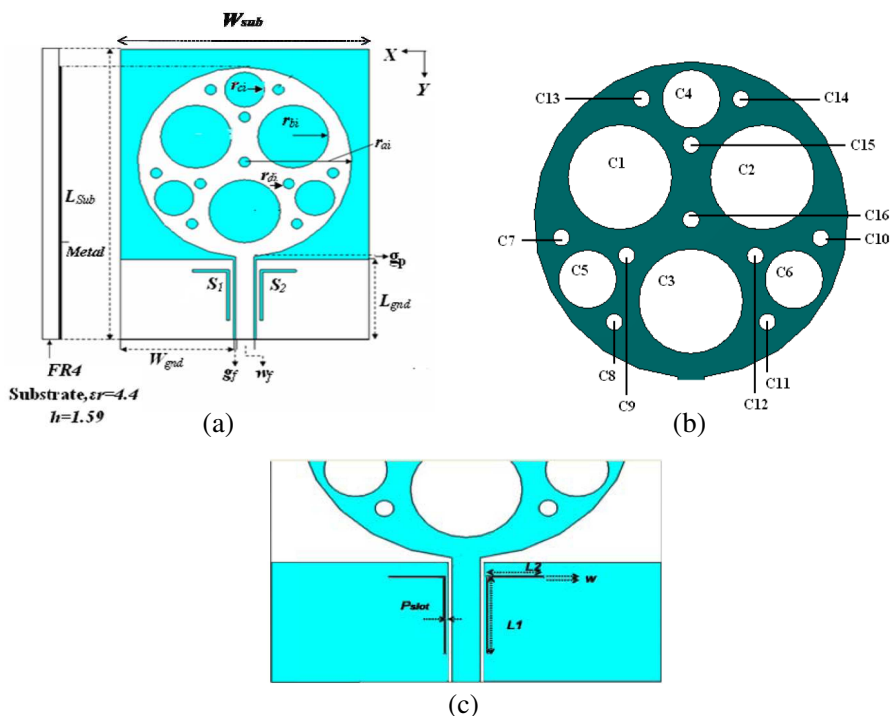


Figure 1. (a) Circular shaped Apollonian fractal antenna of 3rd iteration. (b) Locations of iterated circles on fractal antenna. (c) Dimensions of the L-shaped slot for band rejection.

the antenna diameter has been taken as 38 mm whose center is placed at the origin. It is called initiator or zeroth iteration. The DCT can be applied in the next stage to find out the size of the smaller circle from any set of three original circles. In the 1st iteration, three circles have been taken each of radius 6.3 mm. The radius of these three inner circles is determined by dividing the radius of original circle by $(\frac{3+2\sqrt{3}}{3})$. Then these three circles are subtracted from original circle of radius 19 mm. In the 2nd iteration, three inner circles with radius 3.5 mm each are taken. The radius of these three circles in 2nd iteration is determined by dividing the radius of original circle by $(1 + 2\sqrt{3})$. Again these three circles are subtracted from original circle of radius 19 mm. In the 3rd iteration, ten inner circles of radius 1.5 mm each are taken. The radius of these ten circles in 3rd iteration is determined by dividing the radius of original circle by $(5 + \frac{8}{\sqrt{3}})$. Now these ten circles are subtracted from original circle of radius 19 mm. Using the process stage by stage, it is constructed as a self similar iterative fractal [24] design. Due to fabrication constrains, the design is till 3rd iteration. The locations of all iterated circles are shown in Table 1.

Table 1. Locations of all iterated circles.

Name of the circle	Location of center
C1	-8.618, 5.091
C2	8.618, 5.091
C3	0, -9.83
C4	0, 14.5
C5	-12.5, -7.2
C6	12.5, -7.2
C7	-15.7, -2.2
C8	-9.27, -12.34
C9	-7.8, -4.33
C10	15.7, -2.2
C11	9.27, -12.3
C12	7.8, -4.33
C13	-6, 14.5
C14	6, 14.5
C15	0, 9
C16	0, 0

Figure 1(b) shows one of the two L-shaped slots which are embedded on the CPW ground plane and whose length is close to $\lambda_g/2$ corresponding to the centre frequency of the notch band which is 5.5 GHz for obtaining sharp notching across the desired notch frequency. All the simulations with parametric study have been done by means of a Finite Integration Technique (FIT), using the commercially available CST microwave studio™ [25].

Figure 1(a) illustrates the complete layout of the fractal antenna where the L_{sub} and W_{sub} denote the length and width of the substrate (58 mm × 44 mm), respectively. Gap between the ground plane and feed is (g_f) 0.4 mm. and the feed width (W_f) 3.2 mm is taken for 50 Ω input impedance. The length and width of the ground plane are (L_{gnd}) 15.9 mm and (W_{gnd}) 20 mm respectively. The gap between ground plane and patch is denoted by g_p which is 0.6 mm as it is an important parameter for impedance matching. The length of the notch is $L_s(L_1 + L_2)$ where L_1 is 10.15 mm and L_2 is 6.5 mm and slot width W is 0.2 mm.

It can be noted that there is a shift to lower frequency, for S_{11} dB better than -10 dB, as iteration increases (please refer to Fig. 2). Introduction of fractal shape enhances the effective electrical path [26–29] of surface current which in turn increases the effective impedance bandwidth. This fine tunes the desired impedance bandwidth frequency range of UWB antenna.

Two L-shaped slots S_1 and S_2 , are introduced symmetrically with respect to the feed line of the planner monopole as shown in Fig. 1(b). The two notched frequency of two slots are coupled together and a band stop characteristics with improved notching and desired rejection bandwidth (5–6 GHz) is obtained. Each slot is divided into two sections, L_1 and L_2 from which total length $L_s (L_1 + L_2)$ can be calculated.

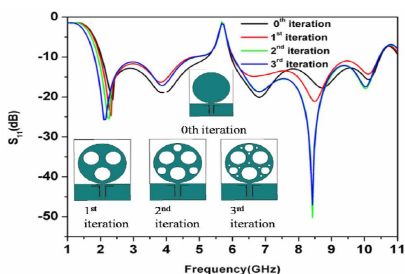


Figure 2. Simulated results of proposed antenna with respect to each iteration.

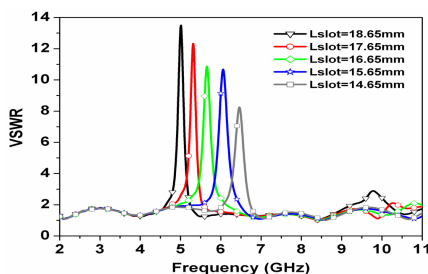


Figure 3. Effect of length of the slots on VSWR.

The resonance frequency of the notch band depends on the length of the slots. Fig. 3 shows that as the length of the slot increases from 14.65 mm to 18.65 mm, the resonance frequency of the notched band shifts towards the lower frequency side. The optimum slot length of 16.65 mm is chosen after parametric study for which the desired notch frequency 5.5 GHz is achieved.

The width of the ground plane (W_{gnd}) has an important role on matching characteristics over the band of proposed antenna. Fig. 4 shows the effect of varying ground plane width which shows as the width is varied from 18 mm to 22 mm, VSWR is not changing significantly but the higher and lower frequency matching is improved. However at middle of the frequency band the performance degrades. In this case an optimum value of W_{gnd} is taken 20 mm as a compromise of all frequency matches perfectly.

To show the dependency of VSWR on the position of the slot, parametric studies have been done for the same. Fig. 5 denotes the variation in peak value of VSWR with changing the position of the slot with other parameters remains constant. It can be seen that the higher the value of P_{slot} , the lower is the value of peak VSWR achieved. An optimum P_{slot} is chosen to be 0.3 mm.

One of the significant parameter is the gap between the ground plane and patch which has tremendous effect on matching. Fig. 6 indicates the variation of VSWR for different gap parameters ' g_p '. The gap is varied from 0.3 mm to 0.7 mm. As the gap decreases it improves the matching throughout the operating band. Further decreasing the gap below 0.4 mm degrades the impedance matching. Gap between ground plane and patch is optimized at 0.6 mm which is proper for impedance matching between feed and the antenna and provides necessary impedance bandwidth.

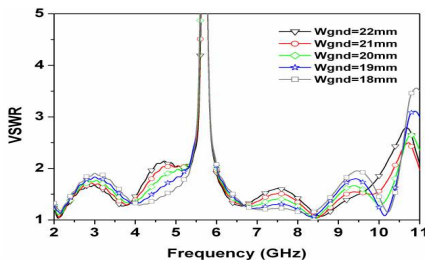


Figure 4. Effect of ground width of the slots on VSWR.

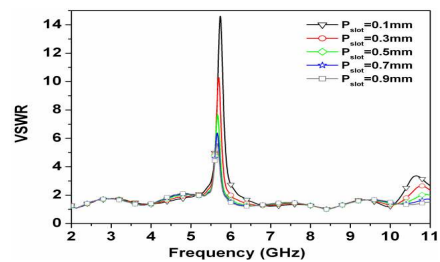


Figure 5. Effect of position of the slots on VSWR.

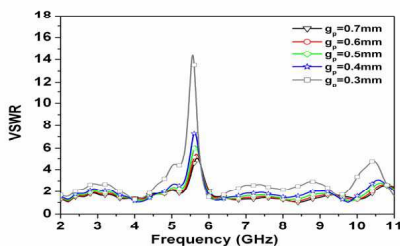


Figure 6. Effect gap between ground plane and patch on VSWR.

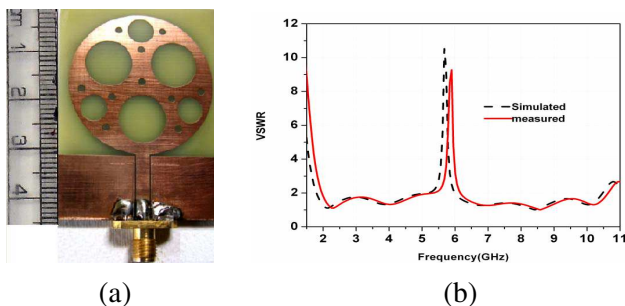


Figure 7. (a) Fabricated prototype of the antenna. (b) Simulated and measured VSWR characteristics of the proposed antenna.

3. RESULTS AND DISCUSSION

Based on the optimized parameters, a fabricated prototype of the proposed antenna is developed, as shown in Fig. 7(a). The dimensions of the antenna and the notch as obtained from parametric study are tabulated in Table 2. The measured and simulated VSWR of the antenna is shown in Fig. 7(b) which is performed using Zhone and Schwarz ZVA 40 VNA.

The antenna provides $VSWR < 2$ over the frequency band of 1.8 GHz to 10.6 GHz and provides a suitable rejection at 5.5 GHz, where as wideband behavior of the antenna is maintained. Thus the antenna possesses very wideband behavior over the desired frequency spectrum. It is seen that the simulated and measured VSWR closely agree, though some discrepancy is observed which occurs due to fabrication tolerance and SMA connector loss.

For UWB applications, the antenna is usually required to have omnidirectional radiation pattern. The simulated and measured copolar and cross polar patterns at frequencies of 3.1 GHz, 7 GHz and

Table 2. Circular shaped fractal UWB monopole antenna design parameters..

Antenna dimensions	Value (mm)	Slot Dimensions	Value (mm)
W_{sub}	44	L_1	10.15
L_{sub}	58	L_2	6.5
L_{gnd}	15.9	W	0.2
W_{gnd}	20		
r_0	19		
r_1	6.3		
r_2	3.5		
r_3	1		
g_f	0.4		
W_f	3.2		
g_p	0.6		

10.6 GHz have been shown in Fig. 8. At lower frequencies, the E -plane patterns are similar as the conventional monopole antenna. But at higher frequency, some ripples are observed in the pattern due to higher order modes. Also at higher frequency, some discrepancy is observed between simulated and measured cross-pol patterns due to substrate losses and measurement setup.

Figure 9 displays the current distribution at frequencies 3.7 GHz, 5.5 GHz and 8.5 GHz. Fig. 9(a) indicates that the current is concentrated through the bottom of the patch and feed line which indicates lower order mode. The current distribution in Fig. 9(b) clearly indicates formation of standing waves at notch frequency as the current is concentrated at the region of L-shaped slots. It is confirmed that the L-shaped slot effectively reflects the signal power back to the input port and thus mismatching occurs. In Fig. 9(c) at 8.5 GHz, current flows at the circumference of the antenna due to higher order modes. It is also noticed that current is concentrated in the gap between patch and ground at all frequencies, which reveals that the gap between patch and ground performs a crucial role in antenna performance.

4. TIME DOMAIN ANALYSIS

UWB impulse radio system is based on short pulse transmission. The proposed antenna has a wide band frequency domain response but

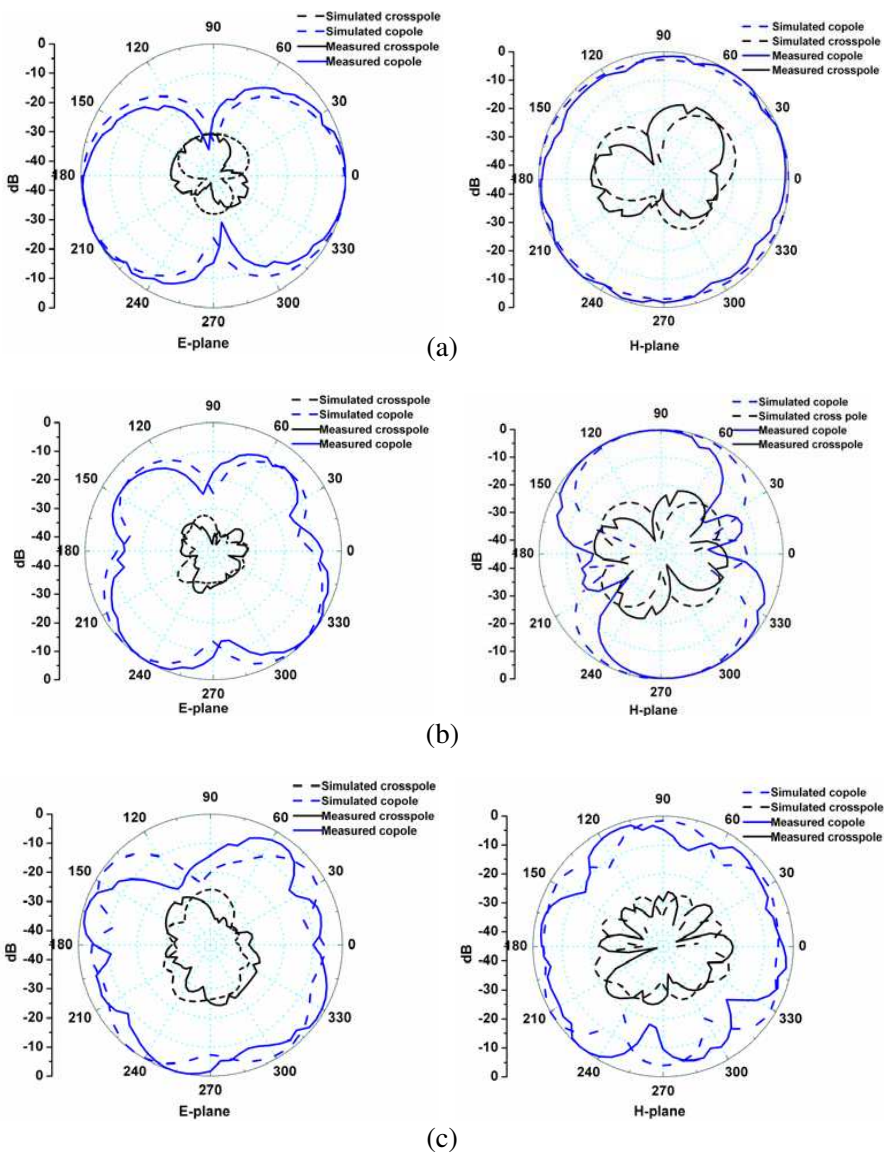


Figure 8. Simulated (dashed) and Measured (solid) radiation patterns of proposed antenna at (a) 3.1 GHz, (b) 7 GHz and (c) 10.6 GHz.

it does not necessarily assure that the antenna behaves well in the time-domain as well. Therefore in order to ensure the usefulness of proposed antenna for time domain application and also to measure

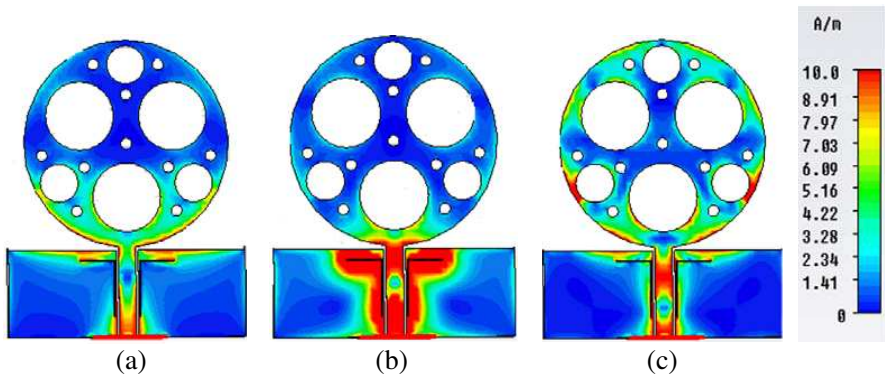


Figure 9. Current distribution at (a) 3.7 GHz, (b) 5.5 GHz, (c) 8.5 GHz.

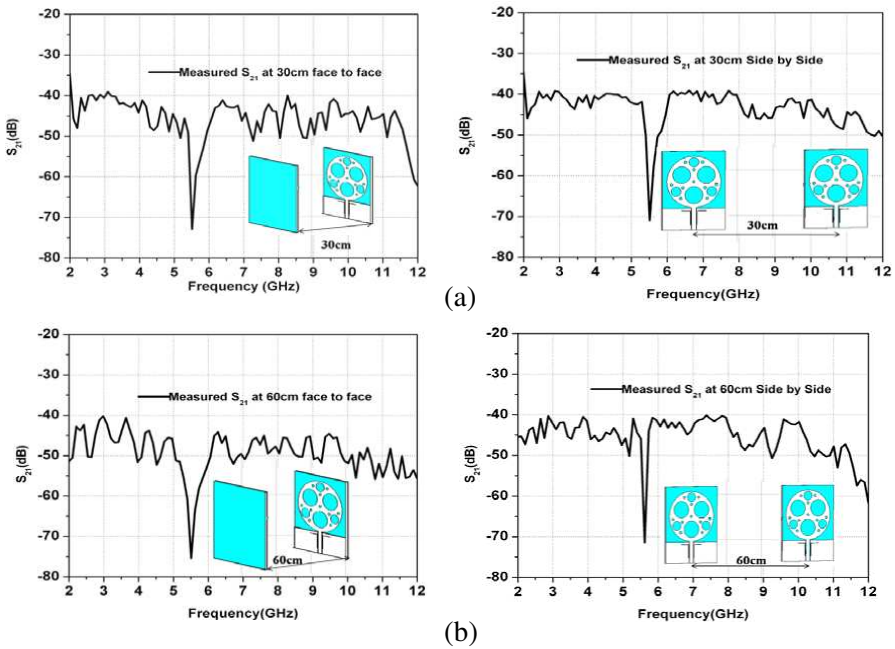


Figure 10. Measured transmission loss of a pair of UWB antenna in face to face and side by side (a) at 30 cm, (b) at 60 cm.

group delay, a pair of identical antennae were mounted on the two ports of the analyzer inside an anechoic chamber where they serve as the transmitting and receiving antenna. To improve the

measuring accuracy, the reference planes were calibrated to the antenna terminals. Fig. 10 represents the measured transmission loss or transfer function [29] of two similar types of fabricated antenna placed face to face as well as side by side at a distance of 30 cm and 60 cm respectively in free space. It can be seen that the S_{21} decreases while the distance between the antennas increases. Almost flat response except some non linearity guarantees the non-distorted reception of the transmitted signal.

UWB antenna should be distortion free. To ensure this, measured group delay is considered here. The variation of group delay is within 1 ns except the notched band where it is very large as shown in Fig. 11. This ensures that this antenna is distortion free and exhibits satisfactory time domain characteristics throughout its operating band.

The correlation coefficient is defined by

$$\rho = \max_{\tau} \left[\frac{\int S_1(t) S_2(t - \tau) dt}{\sqrt{\int S_1^2(t) dt} \sqrt{\int S_2^2(t) dt}} \right] \tag{2}$$

where, $S_1(t)$ and $S_2(t)$ are transmitted and receiving antenna signals, and ‘ τ ’ is the delay. If correlation coefficient is equal to 1, i.e., fidelity reaches its peak, which means transmitted and received signals are perfectly matched. It reflects two signal wave forms are identical to each other and the antenna system does not distort the input signal at all. The correlation coefficient in face to face orientation is 0.851 and with notch is 0.813. In side by side orientation, it is 0.897 and with notch 0.860 respectively.

The measured peak gain curve of the proposed antenna is shown in Fig. 12. It is seen that the gain of the antenna is constant throughout the UWB band except the notch region where it falls to -7.7 dBi.

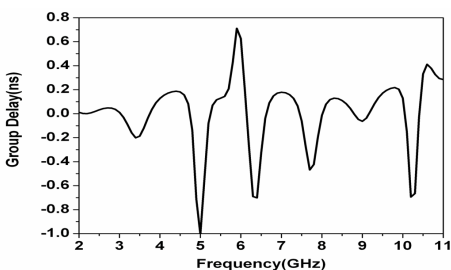


Figure 11. Measured group delay of the proposed UWB band notch antenna.

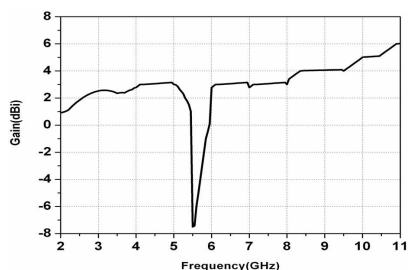


Figure 12. Measured gain profile of the proposed UWB antenna.

5. CONCLUSION

A new circular shaped Apollonian fractal UWB antenna based on Descartes circle theorem has been analyzed and measured. A pair of L-shaped slots is etched from the ground plane for producing the suppression of interference of the WLAN band. The impedance bandwidth ranges from 1.8 GHz to 10.6 GHz showing ultra wideband impedance matching except at the notch band which is at 5.5 GHz. The radiation pattern is omnidirectional. To evaluate the time domain performance of the proposed antenna, the transfer function is obtained by a pair of similar antenna in both face to face and side by side. Correlation coefficient for both orientations is calculated. The measured group delay characteristic exhibits within 1 ns variation over the desired frequency except at the notch band. These ensure distortion free transmission and reception of pulse signals by the proposed antenna. The antenna gain varies from 2 dBi to 6 dBi over the band with dips at the notch band. Total antenna size is 44 mm \times 58 mm.

ACKNOWLEDGMENT

One of the authors Rowdra Ghatak is grateful to Department of Science and Technology, Government of India for supporting this research under Fast Track for Young Scientist vide sanction No. SR/FTP/ETA-0033/2010, dated 31.08.2010. D. R. Poddar is grateful to All India Council for Technical Education (AICTE) for awarding him 'Emeritus Fellow' and supporting this research via grant No. 1-51 RID/EF/(04)/2009-10, dated 06/01/2010.

REFERENCES

1. First Report and Order in the matter of Revision of Part 15 of the commission's Rules Regarding Ultra-Wideband Transmission Systems, Released by Federal Communication Commission ET-Docket 98-153, Apr. 22, 2002.
2. FCC Report and Order for Part 15 Acceptance of Ultra Wideband (UWB) Systems from 3.1–10.6 GHz, FCC Website, Feb. 2002.
3. Zhu, F., S. Gao, J. Z. Li, and J. D. Xu, "Planar asymmetrical ultra-wideband antenna with improved multiple band-notched characteristics," *Electronics Letters*, Vol. 48, No. 11, May 24, 2012.
4. Emadian, S. R., C. Ghobadi, J. Nourinia, M. Mirmozafari, and J. Pourahmadasar, "Bandwidth enhancement of CPW-fed circle-like slot antenna with dual band-notched characteristic," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 2012.

5. Emadian, R., M. Mirmozafari, C. Ghobadi, and J. Nourinia, "Bandwidth enhancement of dual band-notched circle-like slot antenna," *Electronics Letters*, Vol. 48, No. 7, Mar. 29, 2012.
6. Bazaz, R., S. K. Koul, M. Kumar, and A. Basu, "An ultra-wideband antenna with band reject capability and its characterization in time domain," *Progress In Electromagnetics Research C*, Vol. 19, 223–234, 2011
7. Gao, G.-P., Z.-L. Mei, and B.-N. Li, "Novel circular slot UWB antenna with dual band-notched characteristic," *Progress In Electromagnetics Research C*, Vol. 15, 49–63, 2010.
8. Rezaeieh, S. A. and M. Abbak, "A novel compact antenna enhanced with variable notches," *Microwave and Optical Technology Letters*, Vol. 54, No. 4, Apr. 2012.
9. Moosazadeh, M., A. M. Abbosh, and Z. Esmati, "Design of compact planar ultrawideband antenna with dual-notched bands using slotted square patch and pi-shaped conductor backed plane," *IET Microwaves, Antennas and Propagation*, Vol. 6, No. 3, 290–294, 2012.
10. Jiang, W. and W. Che, "A novel UWB antenna with dual notched bands for WiMAX and WLAN applications," *IEEE Antennas and Wireless Propagation Letters*, Vol. 11, 2012.
11. Ghatak, R., R. Debnath, D. R. Poddar, and R. K. Mishra, "A CPW fed planar monopole band notched UWB antenna with embedded split ring resonators," *Loughborough Antennas and Propagation Conference*, 645–647, 2009.
12. Zheng, Z.-A., Q.-X. Chu, and Z.-H. Tu, "Compact band-rejected ultra wideband slot antennas inserting with $\lambda/2$ and $\lambda/4$ resonator," *IEEE Transactions on Antennas and Propagation*, Vol. 59, No. 2, Feb. 2011.
13. Ahmed, O. M. H. and A. R. Sebak, "A novel maple-leaf shaped UWB antenna with a 5.0–6.0 GHz band-notch characteristic," *Progress In Electromagnetics Research C*, Vol. 11, 39–49, 2009.
14. Chiu, C.-W. and C.-S. Li, "A CPW fed band-notched slot antenna for UWB application," *Microwave and Optical Technology Letters*, Vol. 51, No. 6, Jun. 2009.
15. Yazdi, M. and N. Komjani, "A compact band-notched UWB planar monopole antenna with parasitic elements," *Progress In Electromagnetics Research Letters*, Vol. 24, 129–138, 2011.
16. Kalteh, A. A., G. R. Dadash Zadeh, M. Naser-Moghadasi, and B. S. Virdee, "Ultra-wideband circular slot antenna with reconfigurable notch band function," *IET Microwaves, Antennas*

- and Propagation*, Mar. 12, 2011.
17. Li, C. M. and L. H. Ye, "Improved dual band-notched UWB slot antenna with controllable notched band-widths," *Progress In Electromagnetics Research*, Vol. 115, 477–493, 2011.
 18. Jangid, S. and M. Kumar, "Compact planar UWB patch antenna with integrated bandpass filter and band notched characteristics," *IEEE International Conference on Communication Systems and Network Technologies*, 2012.
 19. Addition, P. S., *Fractals and Chaos*, 24–40, Institute of Physics Publishing, Wholly, London, 1997.
 20. Werner, D. H. and S. Ganguly, "An overview of fractal antenna engineering research," *IEEE Antennas and Propagation Magazine*, Vol. 45, No. 1, 2003.
 21. Lagarias, J. C., C. L. Mallows, and A. Wilks, "Beyond the Descartes circle theorem," *Amer. Math.*, Vol. 109, 338–361, 2002.
 22. Liu, J. C., D. C. Chang, D. Soong, C. H. Chen, C. Y. Wu, and L. Yao, "Circular fractal antenna approaches with Descartes circle theorem for multiband/wideband applications," *Microwave and Optical Technology Letters*, Vol. 44, No. 5, 405–408, Mar. 2005.
 23. Naeem Khan, S., J. Hu, J. Xiong, and S. He, "Circular fractal monopole antenna based on Descartes circle theorem for UWB application," *Microwave and Optical Technology Letters*, Vol. 50, No. 6, 1605–1608, Mar. 2008.
 24. Kenneth Flaconer, *Fractal Geometry-mathematical Foundations and Applications*, 1–155, John Wiley and Sons Ltd, England, 1990.
 25. CST Computer Simulation Technology, 2011, <http://www.cst.com>.
 26. Saleem, R. and A. K. Brown, "Empirical miniaturization analysis of inverse parabolic step sequence based UWB antennas," *Progress In Electromagnetics Research*, Vol. 114, 369–381, 2011.
 27. Karmakar, A., S. Verma, M. Pal, and R. Ghatak, "An ultra wide band monopole antenna with multiple fractal slots with dual band rejection characteristic," *Progress In Electromagnetics Research C*, Vol. 31, 185–197, 2012.
 28. Naghshvarian-Jahromi, M., "Novel wideband planar fractal monopole antenna," *IEEE Transactions on Antennas and Propagation*, Vol. 56, No. 12, 3844–3849, Dec. 2008.
 29. Begaud, X., *Ultra Wideband Antennas*, John Wiley and Sons, New Jersey, 2011.