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Compact and Flexible Monopole Antenna for Ultra-Wideband Applications Deploying Fractal Geometry

Geetha G*†, Sandeep Kumar Palaniswamy, M. Gulam Nabi Alsath***, Malathi Kanagasabai* and T. Rama Rao****

Abstract – This paper presents a compact ultra-wideband (UWB) flexible monopole antenna design on a paper substrate. The proposed antenna is made of iterations of a circular slot inside an octagonal metallic patch. This fractal-based geometry has been deployed to achieve compactness along with improved bandwidth, measured reflection coefficient -10 dB bandwidth ranging from 2.7 to 15.8 GHz. The overall size of the antenna is 26 mm×19 mm×0.5 mm, which makes it a compact one. The substrate used is paper and the main features like environment friendly, flexibility, green electronics applications and low cost of fabrication are the key factors for the proposed antenna. The aforementioned UWB prototype is suitable for many wireless communication systems such as WiMAX, WiFi, RFID and WSN applications. Antenna has been tested for the effect of bending by placing it over a curved surface of a very small radius of 10 mm.

Keywords: UWB antennas, Flexible antennas, Fractal antennas, Paper substrate, Conformal antennas

1. Introduction

UWB frequency range has been extensively used since many applications, that include Worldwide Interoperability for Microwave Access (WiMAX), wireless local area network (WLAN), radio frequency identification (RFID), and wireless sensor network (WSN), are concentrated in this frequency band, ranging from 3.1 to 10.6 GHz. Monopole antennas, that offer improved bandwidth and omni-directional radiation pattern have been reported in literature, [1] and [2]. Fractals are mathematical set which exhibits a repeating pattern at every iteration. The aforementioned fractal concept has been used for several types of performance enhancements that include multi banding, size reduction and bandwidth enhancement. In [3], several iterations have been performed on the hexagonal slot performed in the base hexagonal shape. In [4], fractal slots have been incorporated in the ground plane to enhance the bandwidth. In [5] several iterations of the base circular-hexagonal slot have been made for improving the bandwidth of the reported circular-hexagonal antenna. Fractal based tuning stub and slots in [6] and [7] respectively have been used to bring in notch band characteristics. In [8] combination of Giusepe Peano fractal and Sierpinski Carpet fractal have been used, and a Pythagorean tree based fractal has been used in [9]. Several other UWB antenna using fractal concepts and impedance matching property are reported in [10-16]. Although these antennas cover the UWB range, these cannot be used for applications that require, the antenna to be bent over curved surfaces, or in applications that require the prototype to be flexible. This necessitates the usage of non-rigid substrates for the antenna fabrication. In [17] and [18], the monopole antennas are fabricated using paper substrate and in [19], the prototype is developed on a jean substrate. A polyamide based UWB antenna for flexible electronics is designed in [20] and several other antennas for UWB and wideband UHF antenna are demonstrated in [21-23]. The proposed paper substrate antenna, based on fractal concept offers improved bandwidth with further size reduction compared to other flexible antenna in this frequency range. In the proposed work the concept of scaling down a circular slot inside an octagonal patch has been performed till the second iteration.

This manuscript is organized as follows. The design, evolution of the design and parametric study is presented in section II. The simulated and measured results are compared and discussed in section III. Furthermore this section also covers the bending analysis which presents the bandwidth performance of the antenna under unbent and bent conditions. The conclusion is presented in section IV.

2. Antenna Design and Configuration

The antenna is designed on an electrical grade paper substrate of thickness 0.5 mm, permittivity (εr) 3.2 and loss tangent (tanδ) of 0.06-0.07 over the ultra wideband

† Corresponding Author: Department of ECE, College of Engineering, Chennai, India. (geethaceg2015@gmail.com)
* Department of ECE, College of Engineering, Guindy, Anna Univeristy, India. (mala@annauniv.edu)
** Department of ECE, SRM University, Kattankulathur, Chennai, India. (vrpchs@gmail.com, ramaraotr@gmail.com)
*** Department of ECE, SSN College of Engineering, Chennai, India. (alsath@live.com)
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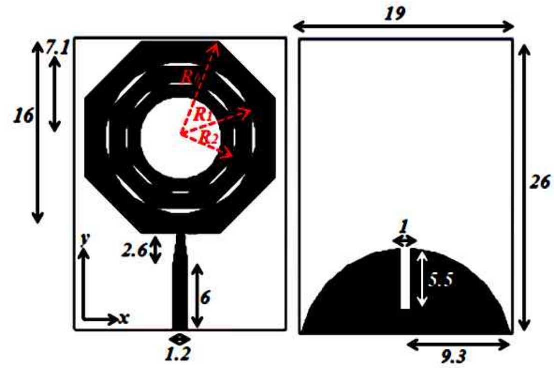

Fig. 1. Dimension details of the proposed UWB fractal-based monopole antenna where R0 - radius of the zeroth iteration (9.2 mm), R1 - radius of the first iteration (6.8 mm) and R2 - radius of the second iteration (5.03 mm). All dimensions are in mm

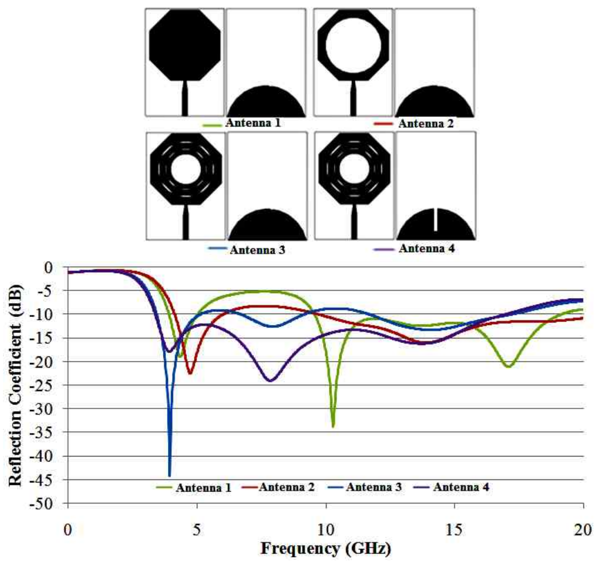

Fig. 2. Evolution of the proposed fractal based monopole antenna and the corresponding reflection characteristics

[18]. Double sided conductive copper tape of thickness 0.035 mm, has been used as the conductive material over the paper substrate. The copper tape at the top acts a radiator, the copper tape at the bottom acts as a ground. The manufacturing process of the proposed antenna is described as follows. At first, the proposed radiator shape is sketched and etched out from the self adhesive dual sided copper tape using micromachining process and then it is pasted on the electrical grade paper substrate. The dimension details of the proposed antenna are presented in Fig. 1. The simulations are carried out using EM full wave analysis tool, CST Microwave Studio 2015.

The design evolution of the proposed fractal based monopole antenna is shown in Fig. 2. Initially an octagonal patch with tapered feed and semi-elliptical ground plane is developed (Antenna 1). The presented antenna structure is

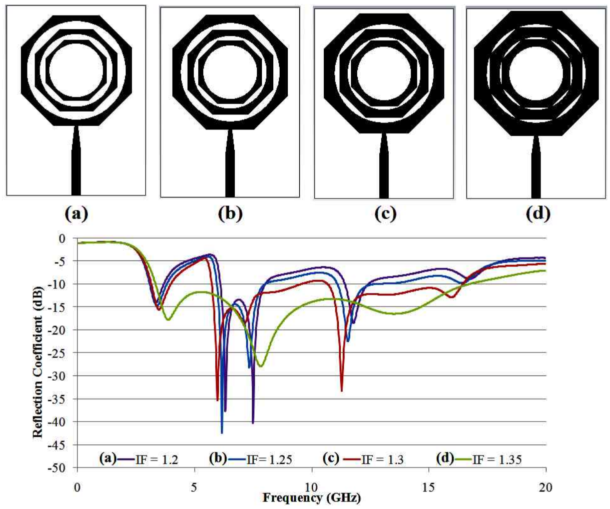

Fig. 3. Iteration Factor (IF=R0/R1=R1/R2=....= Rn/Rn+1) evolution of the proposed fractal based monopole antenna.(a) IF = 1.2, (b) IF = 1.25, (c) IF = 1.3 and (d) IF = 1.35

responsible for the wide band frequency response. In order to further improve the impedance matching at lower frequency edge and to enhance the reflection coefficient characteristics in the upper portion of the frequency band, circular slot is etched in the fundamental patch resulting in an octagonal-circular slot loop (Antenna 2). This is considered as the base Antenna or the reference antenna. In order to obtain large impedance bandwidth with further size reduction and to shift the lower band edge frequency, two iterations of this reference antenna are performed as described by Antenna 3. Further improvement in the frequency response is achieved using the rectangular slot loaded on to the ground plane (Antenna 4). The effect of the ground plane modifications and loading is to broaden the resonances, reduce their peak resistance and to load the centre frequencies down slightly. From the evolution it can be noticed that the Q factor of the antenna gets reduced which in turn broadens the bandwidth of operation as a result the impedance is closer to 50 ohm over a wide bandwidth. This reduction in the Q factor is attributed to the inductive slot loading at the ground and capacitive coupling at the radiator aperture.

The reflection coefficient response for various iteration factors is illustrated in Fig. 3. From the figure, it is inferred that with an increase of IF from 1.2 to 1.35, an improvement in bandwidth along with an improvement in reflection coefficient characteristics is achieved. Thus IF = 1.35 is chosen as an optimum IF for the radiator to achieve UWB characteristics. The reflection coefficient responses of the zeroth, first and second iteration are depicted in Fig. 4. From the figure, it is seen that with an increase in each iteration order, improvement in impedance matching and better reflection coefficient characteristics is attained. The final prototype with the rectangular slot loading in the ground plane is responsible for providing improved

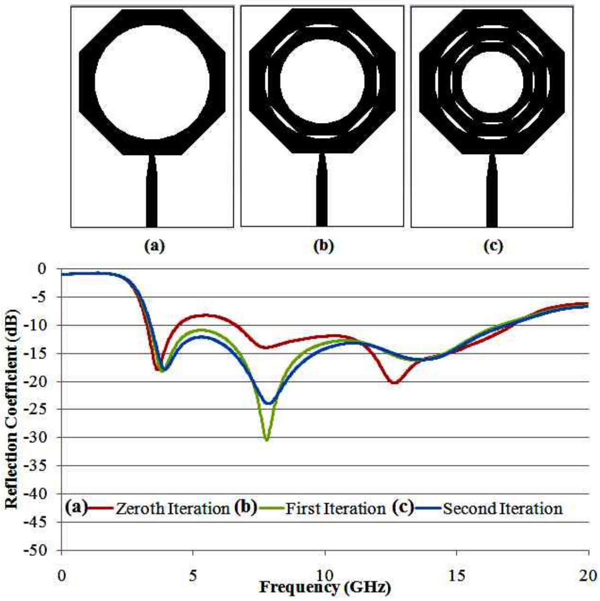

Fig. 4. Iteration order Evolution of the proposed fractal based monopole antenna: (a) Zeroth iteration, (b) First iteration and (c) Second iteration

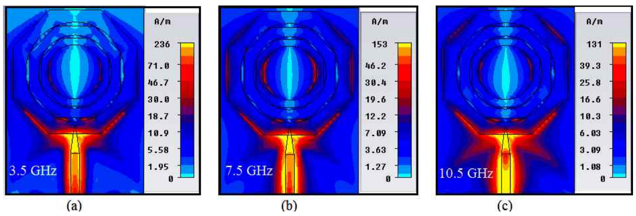

Fig. 5. Magnitude plot of surface current distribution at (a) 3.5 GHz (b) 7.5 GHz (c) 10.5 GHz

bandwidth from 3.1 to 17 GHz.

The surface current distribution for the proposed antenna is plotted in Fig. 5. The figure shows the region of dense current at different portions of the antenna at different frequency points. Thus from the figure it is inferred that the fractal geometry is responsible for attaining large impedance bandwidth.

3. Results and Discussions

The simulated and measured reflection coefficient characteristics of the proposed UWB antenna are shown in Fig 6. It is clearly seen that the proposed antenna has a wide impedance bandwidth (at -10 dB of |S11|) from 3.1 GHz to 17 GHz in simulation and in measurement the bandwidth (at -10 dB of |S11|) from 2.7 GHz to 15 GHz is obtained.

The photograph of the fabricated prototype (front and rear view) and the measurement scenario depicting the various bending orientations is presented in Fig. 7. The bending is done in both horizontal (X) and vertical (Y)

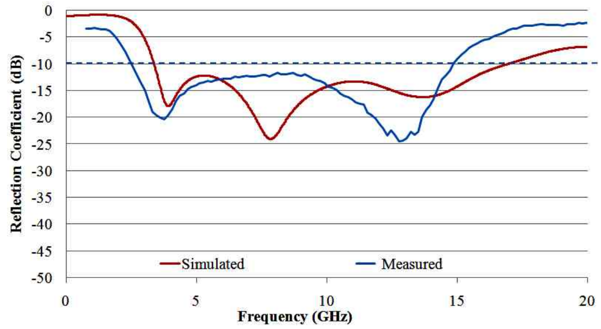

Fig. 6. Simulated and measured reflection coefficient characteristics of the proposed antenna.

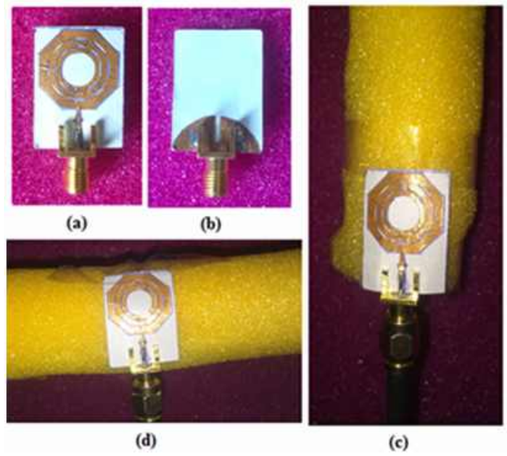

Fig. 7. Photograph of the fabricated prototype under flat and bent conditions (a) Front view (b) Rear view (c) X- bent, and (d) Y- bent

axes. These examinations will help to understand the effect of bending on the antenna's performance. The antenna deployed in harsh environmental conditions should provide stable impedance and radiation characteristics. The prototype antenna is bent along X and Y planes over the foam medium with dielectric constant 1.07 at 10 GHz, radius of curvature 10 mm, so as to study the maximum bending effects for a small dimensioned paper based monopole antenna. The measurements are performed using ENA Series E5071C Vector Network Analyzer. From the results it is evident that, the measured S parameter reflection coefficient results are still within the acceptable level. The ripples in the measured results are attributed to the stretching effects of the paper substrate which alters the electrical properties. The reasons can also be attributed to the SMA connectors and the associated cables used during the measurement process.

The measured reflection coefficient characteristics of the prototype antenna under flat and bent conditions are depicted in Fig. 8. The reflection coefficient characteristics of the antenna bent along x-axis follows a similar trend as that of an unbent antenna. However, due to a very small radius of curvature, in y-bend scenario the surface current

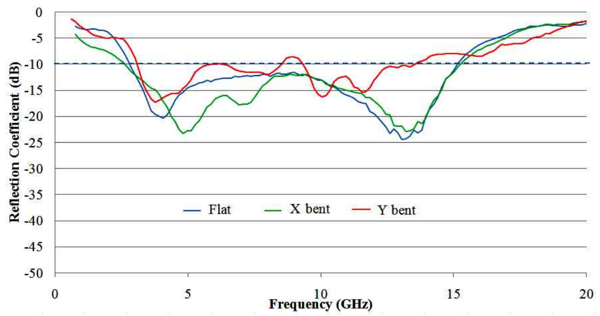

Fig. 8. Measured reflection coefficient characteristics of the prototype under flat and bent conditions

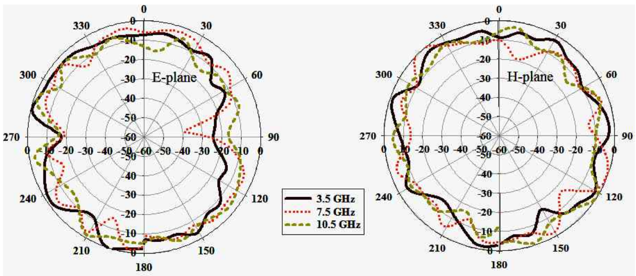

Fig. 9. Measured radiation pattern of the proposed antenna along E-plane (yz-plane) and H-plane (xz-plane) at 3.5 GHz, 7.5 GHz and 10.5 GHz

along the feed is disturbed, causing a small notch in the reflection coefficient characteristics around 9 GHz. The measured E and H- plane pattern plots of the proposed prototype at three different frequencies (3.5 GHz, 7.5 GHz, and 10.5 GHz) are plotted in Fig. 9. A near omni-directional radiation pattern can be observed in all the frequencies, satisfying the UWB monopole radiation pattern specifications.

The simulated and measured gain along with the simulated radiation efficiency of the proposed paper substrate antenna is presented in Fig. 9. From the results, the antenna offers a gain variation of 0.1 dB to 2.7 dB across the frequency range of 2.7 – 15.8 GHz while it occurs the highest values of 2.7 and 2 dB at the vicinity of 6 GHz and 14 GHz, respectively. The measured gain values for 3.5 GHz, 5 GHz, 7.5 GHz, 10 GHz and 12.5 GHz are 2.5 dBi, 2.3 dBi, 1.5 dBi, 0.8 dBi and 0.75 dBi respectively. The proposed antenna has the radiation efficiency greater than 60% throughout the operating band. The gain of the proposed prototype is less due to the small thickness of the substrate, high loss tangent value of the paper substrate. An average efficiency of 74% is obtained in the UWB, from Fig. 10. The group delay of the proposed antenna is shown in Fig. 11. It is noted that the group delay of the antenna is almost flat over the entire operating band. The variation in time or delay of the frequency components of the transmitted/received signal is less than 0.5 ns for the entire operating band starting from 2.7 to 15 GHz. It is almost constant for all frequencies which shows that all frequency components of the transmitted pulse remain intact, shows the better performance of the proposed antenna in terms of UWB characteristics.

Table 1. Performance comparison of the proposed antenna with the other flexible UWB antennas reported in literature

S. No.	Ref. No.	Size (mm^2)	Bandwidth (GHz)
1.	[16]	13 × 30	3.6
2.	[17]	20 × 26	10
3.	[18]	60 × 60	11.5
4.	[19]	58 × 58	13
5.	[20]	47 × 33	12
6.	Proposed Work	26 × 19	13.7

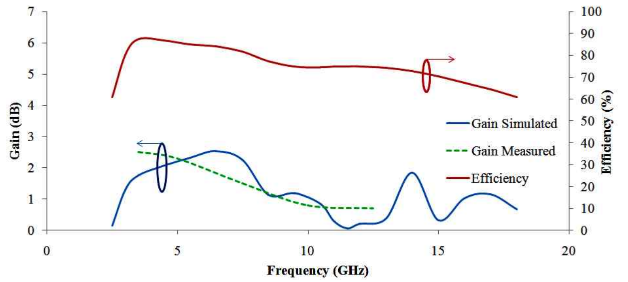

Fig. 10. Gain and efficiency of the proposed paper substrate antenna

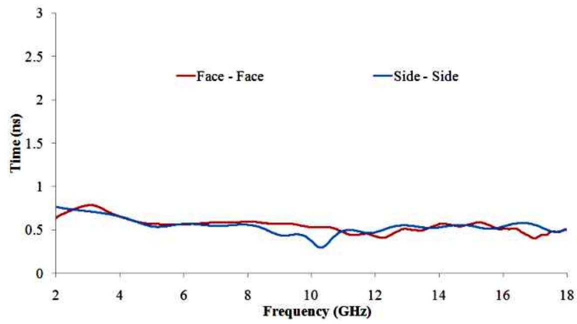

Fig. 11. Group delay of the proposed antenna (face- face orientation and side-side orientation)

A comparison between the performances of the proposed antenna with the other flexible UWB antennas reported in literature is presented in Table 1. From the table, it is evident that the proposed antenna is one of the compact solutions available in literature. Also, the antenna prototype offers an improved bandwidth covering the entire UWB range compared to the other reported flexible antennas in literature. Moreover, the bending is performed by keeping the prototype around a foam cylinder of very small radius 10 mm and when bent over x and y planes, a tolerable undeterred performance are obtained.

4. Conclusion

This paper presented the design of a planar, low profile, compact and flexible UWB monopole antenna constructed using copper tape and paper substrate. The paper substrate and the copper tape, provide the property of flexibility for the proposed antenna prototype. The impedance bandwidth of the antenna is enhanced using fractal geometry. The antenna is designed and simulated using commercial full wave EM solver. The prototype antenna is fabricated and measurements are performed. The measured bandwidth, ranging from 2.7 to 15 GHz is observed under unbent conditions. The bandwidth performance of the proposed antenna remains almost stable even under extremely bent conditions, making the proposed prototype a suitable candidate for flexible and conformal applications. The time domain analysis of the antenna is carried out and the results are reported. The group delay variation of the proposed paper substrate antenna is less than 0.5 ns throughout the UWB range when placed in face to face and side to side orientations. From the obtained results, it can be concluded that the antenna is suitable for UWB wireless standards.

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Geetha G She completed her Ph.D. degree in Optical Communication from the Department of Electronics and Communication Engineering, College of Engineering Guindy, Anna University, Chennai. She is currently an Associate Professor in the Department of Electronics and Communication Engineering, Anna University, Chennai. Her research interests are satellite communications, Radio Frequency, microwave engineering, optical technology and planar antennas.

Sandeep Kumar Palaniswamy He completed his Ph.D. degree in Antenna Engineering from the Department of Electronics and Communication Engineering, College of Engineering Guindy, Anna University, Chennai. He is currently working as an Assistant Professor in the Department of Electronics and Communication Engineering at SRM University, Chennai, India. His research interests include Planar antennas, Monopole antennas, Wideband antennas, Conformal antennas, Antenna measurements, Microwaves, MIMO antennas and 3D antennas.

M. Gulam Nabi Alsath He completed his Ph.D. degree in Antenna Engineering from the Department of Electronics and Communication Engineering, College of Engineering Guindy, Anna University, Chennai. He is working as an Associate Professor in the Department of Electronics and Communication Engineering, SSN College of Engineering, Chennai. His research interests include design of reflector antennas, planar antennas, multiband antenna structures, and antennas for vehicular applications.

Malathi Kanagasabai She completed her Ph.D. degree in Microwave Engineering from the Department of Electronics and Communication Engineering, College of Engineering Guindy, Anna University, Chennai. She is currently an Associate Professor in the Department of Electronics and Communication Engineering, Anna University, Chennai. Her research interests include microwaves, transmission lines, antenna structures, and high speed systems.

T. Rama Rao He completed his Ph.D. degree in Radio Communications from Sri Venkateswar University, Tirupati, Andhra Pradesh, India. He is currently a Professor of Telecommunication Engineering at SRM University, India, and has a long-standing research experience on Radiowave Propagation Studies for Mobile & Wireless Communications. His research interests include high performance millimeter-wave antennas at 60 GHz and associated transceiver circuit for gigabit wireless applications, inter-satellite radio link investigations at millimeter-waves and wearable antennas.