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Design of a Novel Antenna and Its Characterization in Frequency and Time Domains for Ultra Wide Band Applications

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Abstract—A novel compact planar monopole antenna for UWB applications is proposed in this paper. The proposed novelty of the antenna is attributed to the addition of suitable beveled stubs to a basic circular geometry of the radiator as an improved impedance matching technique to achieve enhanced radiation performances. The feed circuit is a tapered microstrip line with a matching section over a semi-elliptical ground plane. The proposed antenna achieves sufficient impedance bandwidth for a VSWR < 2 for frequencies from 3–15 GHz covering the entire UWB range (3.1–10.6 GHz), which is verified experimentally. Also this design achieves good gain, constant group delay and a near omni-directional radiation pattern over the UWB band. The UWB characteristics of the antenna are evaluated in frequency and time domains. Results reveal that the proposed antenna has flat transfer function, linear phase and good impulse response with virtually no ringing which are the essential requirements for an UWB antenna for efficient pulse transmission/reception. The simulated and measured results of these parameters are presented. The performance results of the novel antenna with other designs is also compared and presented.

1. INTRODUCTION

Ultra Wide Band (UWB) technology opens new doors for wireless communication systems as the current wireless systems suffocates for bandwidth. The allocation of the unlicensed use of the UWB bandwidth from 3.1 to 10.6 GHz by the Federal Communications Commission [1] led to the development of various devices for operation in that band. As antennas are the eyes and ears of any system, they should function properly in that band for the devices successful transmission/reception of signals.

UWB technology uses pulses of very short duration in the range of few pico-seconds such that the pulses occupy a very large bandwidth. The antenna used for transmission of such pulses should allow this much bandwidth signals through them with minimum loss of information for efficient pulse transmission. The antennas used for UWB applications should be simple in structure, low cost, easy to fabricate for mass productions and have omni-directional radiation properties.

Planar monopoles prove themselves to be an asset for such applications; hence modifications to planar monopoles have been done in terms of bandwidth enhancement techniques and pulse transmission characteristics.

In [2], a rectangular planar antenna with addition of an extra patch on substrate backside as a bandwidth enhancement technique is proposed. An elliptical slot antenna with concentric circular stub for tuning and graded feed for impedance matching is proposed in [3]. Although these designs match antenna impedance in the desired band, they fail to demonstrate the UWB characteristics of the antenna. The papers [4–8], use fractals in their antenna design such as Pythagorean tree, Sierpinksi Carpet Rectangle, Sierpinksi Carpet Circle, Diamond geometries.

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Fractals are used in these designs to achieve multi-band operation. Increasing the fractal iterations has increased the resonant modes. However, increasing fractal iterations increase the complexity of the design and they exhibit dispersive behavior. A UWB antenna should be alleviated from dispersive behavior for minimum pulse distortion. Circular disc monopoles are promising structures for ultra wide band performance, have good radiation characteristics and tend to be non-dispersive. But, their operation band is limited to 10 GHz and as frequency increases antenna impedance matching becomes difficult to achieve and ultimately they exhibit reduced gain and radiation performances [16]. Having these in mind, circular geometry is chosen as the base for this proposed antenna design as they are non-dispersive. Furthermore to alleviate the inherent limitations of these types of structures to support for UWB applications, a novel antenna is proposed with improved impedance matching technique for wide impedance match.

In this paper, a novel planar antenna is proposed for UWB pulse transmission/reception in the frequency range from 3–15 GHz. The antenna is designed by adding suitable beveled stubs to the circular geometry for improved impedance matching and proper notches are cut out to incorporate bandwidth enhancement techniques for wide impedance bandwidth. The frequency and time domain characterization of the UWB antenna for impulse communications are simulated and the results are presented to demonstrate the antenna performance.

2. PROPOSED ANTENNA DESIGN DESCRIPTION

The proposed antenna geometry is displayed in Figure 1. The antenna design is modified from circular geometry to have a flat base to support for beveling technique and tapered feed for wide impedance match. The optimization of this base is done to achieve improved impedance bandwidth by smooth impedance transition [9]. As this part of the radiator is very critical for governing the capacitive coupling with the ground plane, any reshaping of this part affects the current path strongly [10]. Further the antenna base is beveled to shift upward the upper edge frequency of the antenna by proper design [10–13]. Five arms in the shape of an equilateral triangle of sides ‘a’ chosen by parametric study are added as stubs and equally spaced around the periphery of the antenna for providing inductive reactance to counter-effect the strong capacitive reactance offered by the bottom portion of the antenna. Slots of width 1 mm are etched in the centre portion of these five arms to manipulate the reactance offered by them and to have sufficient impedance match.

Stubs of equal length are chosen and they are placed symmetrically along the patch to have a symmetrical configuration, such that the effective center of the antenna remains close to the physical center so that the feed point impedance sees a 50-ohm match. Symmetrical loading of the antenna by

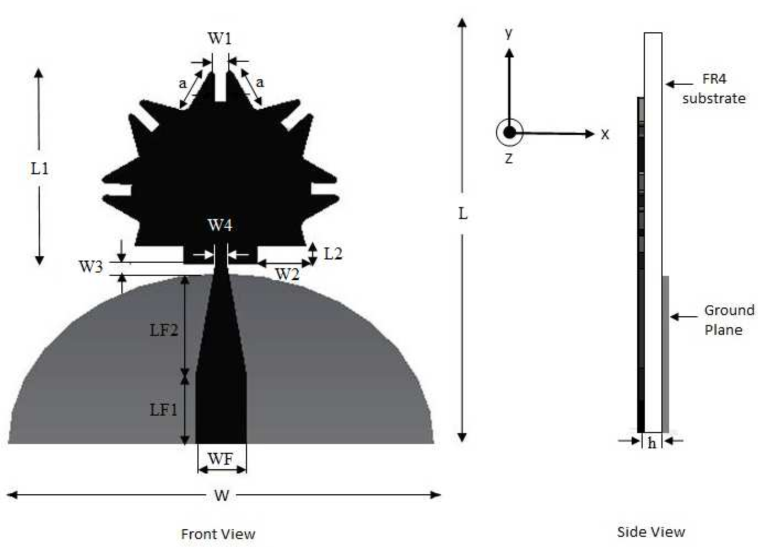

Figure 1. Structure of the proposed antenna.

stubs are done to reduce cross-polar levels. Stubs of the same length are chosen to avoid the variation in impedance offered by them and for symmetry.

Basically an antenna with sharp cuts and bends tend to radiate more. Current passing through such design easily finds its way to radiate through free space. The pointed edges of these arms increase the radiation resistance of the antenna such that the transition of accelerated charges from the antenna as electromagnetic waves into free space becomes easy. Edges of these arms are blended by an amount by parametric study so that these sharp edges do not produce any adverse Group Delay variation when approaching high frequencies.

The antenna is fabricated on a FR4 substrate of dimensions ($L \times W$) with relative permittivity ($\varepsilon_r = 4.3$), whose thickness is h and a loss tangent ($\tan\delta$) of 0.025. The antenna is designed with a partial ground plane and a feed line of 50-Ω characteristic impedance. The dimension details of various parameters are given in Table 1.

Table 1. Design parameters of the proposed antenna.

Parameters	Dimensions (mm)
L	35.5
W	34
L_1	15.5
L_2	1.5
L_{F1}	5.5
L_{F2}	9
a	3
W_1	1
W_2	4
W_3	0.75
W_4	0.41
W_F	4
h	1.6

The partial ground plane is chosen of the semi-ellipse shape in order to obtain linear phase characteristics of the reflection co-efficient for transmission/reception of narrow pulses in UWB systems to achieve nearly constant group delay across the frequency band [14]. The size of the ground plane is crucial in achieving the ultra wide bandwidth. The ground plane size is chosen such that the distance between the top part of the ground plane and the bottom part of the radiator is optimum for reduction in surface current reflections. And the feed line is tapered to match the impedance of the feed line to the antenna impedance by a smooth taper transition from the feed line to the antenna such that the feed line impedance gradually approaches the antenna impedance and finally matches. Two notches of dimensions ($W_2 \times L_2$) are etched on both sides of the lower corners of the radiator for bandwidth enhancement. The discontinuity occurred from cutting notches at the bottom side of the antenna enforces the vertical current mode which leads to improved impedance matching performance at higher frequencies [15]. It also ensures the polarization purity of the radiated electromagnetic signal by reducing the cross-polar radiation from the antenna.

3. RESULTS AND DISCUSSION

The proposed antenna design is finalized by choosing the optimum parameters for the desired UWB performance determined by parametric study. The finalized antenna design is fabricated and measured.

A photograph of the fabricated antenna is shown in Figure 2 with the patch radiator on the front view and semi-elliptical partial ground plane on the back view. SMA connectors were soldered to the

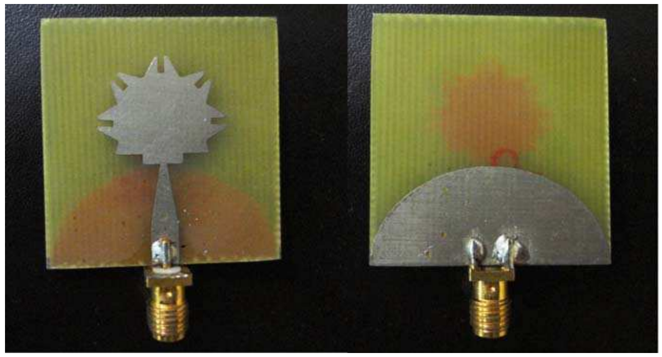

Figure 2. Photograph of the fabricated antenna.

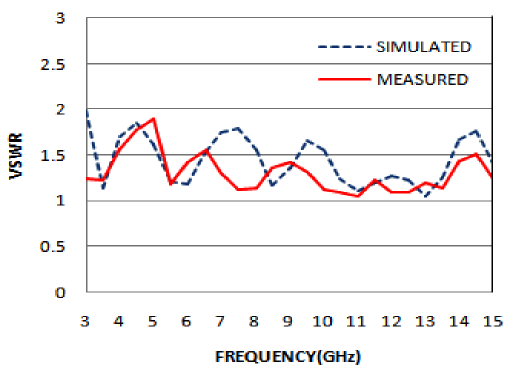

Figure 3. VSWR of the proposed antenna.

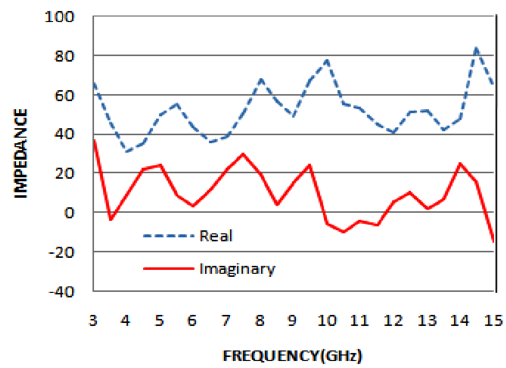

Figure 4. Input impedance of the antenna.

feed line for energizing the structure. Figure 3 illustrates the simulated and the measured VSWR of the antenna. It can be seen from the figure that simulated results coincide with the measured one. Both the curves show that the antenna achieves a bandwidth from 3–15 GHz. The VSWR curve remains below value 2, which ensures that the antenna impedance is well matched over and above the UWB bandwidth. Some discrepancies between simulated and fabricated results may be due to fabrication tolerances, feed connector misalignment and substrate variations due to frequency. The simulated real and imaginary parts of the antenna input impedance is shown in Figure 4. The real part contributes to the radiation resistance of the antenna and the imaginary part defines the mismatch. As the input impedance is matched to 50-Ω through the tapered feed line the real part grazes around 50 Ω and the imaginary around 0 Ω respectively, which again shows the good impedance match of the antenna. This shows that the antenna stores less energy, as reactance is nearly zero and radiates more energy into free space as resistance of the antenna is matched to 50 Ω.

The gain of the proposed antenna is shown in Figure 5. Fairly good gain is achieved throughout the UWB band, which is yet another important criterion a UWB antenna has to fulfill. The antenna achieves a maximum gain of 5 dB.

Compared to the classic circular disc monopole design [16], which has radiator in the shape of a simple circle without any modifications to the geometry, the proposed novel antenna with improved impedance matching techniques achieves a constant gain throughout and above the UWB band.

The simulated impulse response of the proposed antenna is shown in Figure 6. The input pulse is a fifth derivative of a Gaussian pulse which has spectral components in the frequency range 3–11 GHz. Such a pulse is chosen to excite the antenna so as to comply with the Federal Communication Commission (FCC) defined emission mask standards [17]. The input pulse and the impulse response of the antenna are shown in the same graph so as to compare the input and transmitted pulse shapes. The harmonics of the pulse, right from the lower edge of the band to the upper edge gets transmitted effectively without distortion, which can be seen as the transmitted pulse preserves the pulse shape of

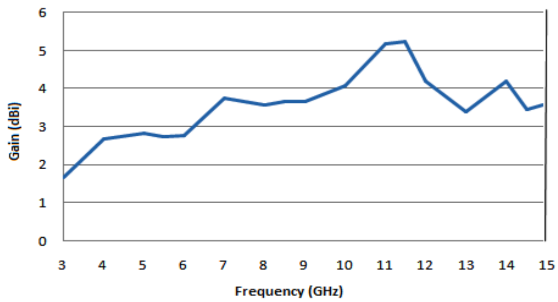

Figure 5. Gain of the antenna.

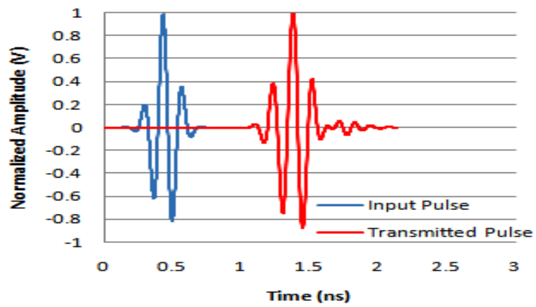

Figure 6. Impulse response of the antenna.

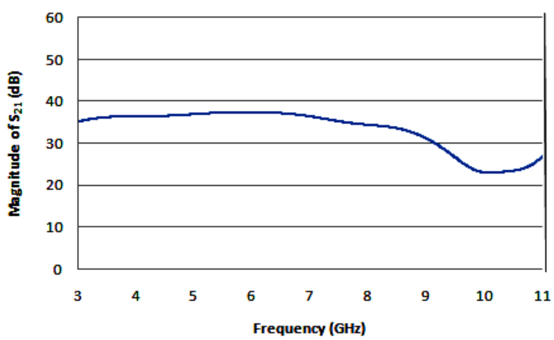

Figure 7. Magnitude of transfer function.

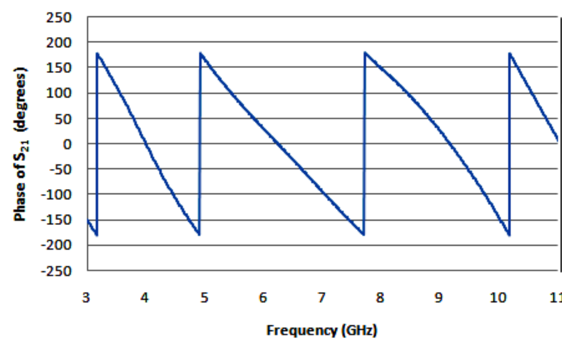

Figure 8. Phase of transfer function.

the excited input pulse. From the transmitted pulse it is also observed that it has no ringing at all. The proposed antenna has enough bandwidth to let all the harmonic frequency components of the signal to pass through without any attenuation of the pulse which enables effective pulse transmission/reception for the UWB applications.

UWB systems use narrow pulses of very short duration for transmitting signals. Hence, the transfer function is crucial to evaluate the proposed antenna performance for efficient transmission of such pulses. By considering the antenna system as a two-port network, the transmission scattering parameter S_{21} of the antenna is plotted in simulation [18]. Virtual recording probes, which act as ideal receivers are placed at a distance of 100 mm from the antenna in a face to face orientation for measuring the transmission characteristics. Antenna functions as Port 1 and Probes function as Port 2. The transmission characteristics between them is recorded and plotted.

The simulated magnitude and phase of the transmission scattering parameter which indicates the antenna transfer function are shown in Figures 7 and 8.

The magnitude of the transfer function should be frequency flat over the operation band. The magnitude plot of transfer function of the proposed antenna shows that it is nearly flat till 9 GHz. After that less than 10 dB variation is observed between 9–11 GHz. The overall response can be considered almost flat over the entire UWB band. Similarly, the phase of transfer function should vary linearly over the operation band. Transfer function phase of the proposed antenna is perfectly linear over the entire band. From the magnitude and phase plots of the transfer function of the proposed antenna it is confirmed that the antenna is suitable for UWB impulse communications.

Group delay is an important parameter to characterize the UWB antenna behavior. It measures the degree of distortion of signal waveforms. The Group delay graph of the proposed antenna is illustrated in Figure 9. The Group Delay of the antenna is almost flat over the UWB frequency range. The variation in time or delay of the frequency components of the signal is less than 0.25 ns for the whole UWB band.

It is constant for all frequencies which show all frequency components of the transmitted pulse

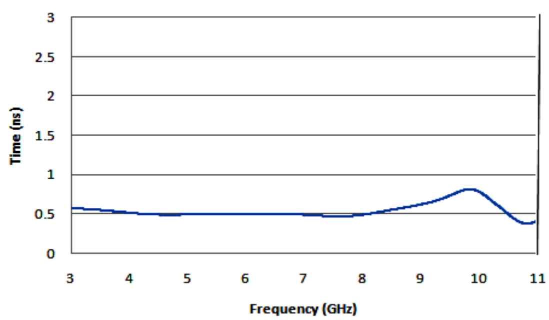

Figure 9. Group delay of the antenna.

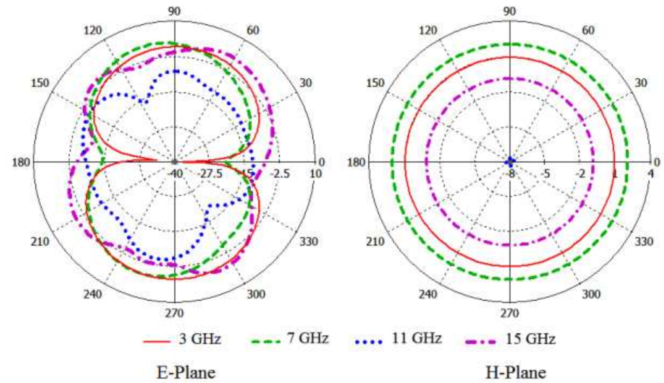

Figure 10. Simulated radiation patterns.

Table 2. Performance comparison of proposed design with different antennas in the literature.

Antenna	Size (mm^2)	Bandwidth (GHz)	Group Delay (ns)	Gain Variation (dB)
Conventional CDM [16]	42 × 50	7	-	−7 to +7 (∼14)
CPW fed patch [19]	25 × 25	10.44	1	-
Ring Monopole [20]	23.6 × 40	30	50	−5 to +8 (∼13)
Novel	34 × 35.5	12	0.25	+1.8 to +5.2 (∼3.4)

remain intact, which in effect shows the superior performance of the proposed antenna in terms of UWB characteristics compared to many other antennas in the literature [19, 20], whose comparison is shown in Table 2 later in this section.

Figure 10 shows the simulated radiation patterns of the antenna in the E-plane and the H-plane for four different frequencies throughout the band 3, 7, 11 and 15 GHz. In the E-plane the antenna preserves the shape of a dumb-bell and in the H-plane it is in the form of a circle which dictates the omni-directional behavior of the antenna. At low frequencies the pattern in E-plane exhibit doughnut shape radiation pattern, as the frequency of operation of the antenna increases the patterns become somewhat directional which is attributed to the classic monopole behavior of the antenna. However, the patterns are constant over the band which is yet another essential requirement for UWB applications.

The simulated surface current distribution of the proposed antenna depicted in Figure 11 allows the understanding of the radiation mechanism of the antenna. At 3 GHz the current strength is mainly along the feed line, ground nearer to the feed and the lower part of the radiator. Currents from this section contribute to radiation at lower frequencies. As the frequency increases, as observed at 7 GHz, drastic change in current distributions occur as currents start to spread out through the whole structure and radiation from the lower edge of the radiator and upper part of the ground plane is predominant. From the port, the currents travel along the feed line upwards towards the radiator, and then the flow changes direction and takes the return path from the outer edge of the ground plane towards the port. While at 11 and 15 GHz, surface currents group along the outer edges of the radiator and top portion of the ground plane near to the radiator. These current distributions contribute to the far field radiation patterns of the antenna.

Table 2 shows the performance comparison of novel design with other designs in the literature. The table depicts the distinctive differences that compared to the conventional CDM design; the novel antenna has achieved reduction in size and has a large bandwidth which more than suffices the UWB bandwidth requirement. However, the novel design has a size greater than the other two antennas reported in [19, 20]. The objective of the proposed antenna design is to improve the essential UWB characteristics of the antenna in terms of constant gain and group delay with the sufficient impedance bandwidth. Size has been compromised for this (compared to the other two antennas) to enhance the more important UWB behavior of the antenna.

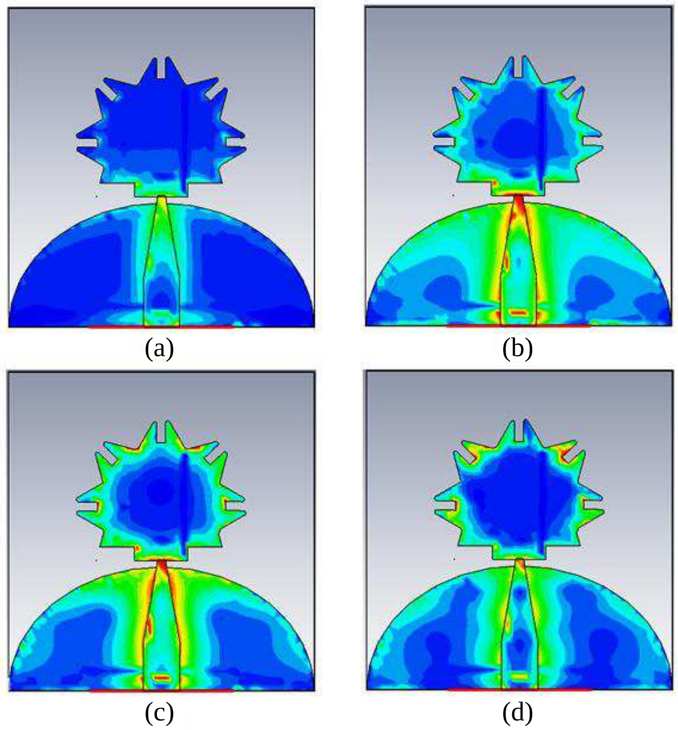

Figure 11. Simulated surface current distributions of the proposed antenna. (a) 3 GHz. (b) 7 GHz. (c) 11 GHz. (d) 15 GHz.

Group delay, an essential parameter which decides the UWB antenna performance is the least for the proposed design (almost constant) as desired, compared to all the other antennas reported in [16, 19, 20]. And the range of values in which the gain varies is also the least for the novel design compared to the other antennas ([16, 19, 20]) which shows that power gets distributed more evenly at all frequencies. The overall performance comparison of the novel antenna with other designs shows that novel design has better UWB characteristics than the previously reported designs.

4. CONCLUSION

A novel compact planar monopole antenna for UWB applications is proposed in this paper.

This design achieves ultra-wide bandwidth from the frequency range 3–15 GHz, ensuring proper function of the antenna in the UWB band, which is verified experimentally. The proposed antenna has good gain and omni-directional radiation pattern over the operating band. Furthermore, the study of UWB characteristics of the antenna is conducted in frequency and time domain. The design exhibits constant group delay, flat transfer functions and phase linearity in frequency domain and good impulse response in time domain with virtually no ringing, which ensures minimal distortion of signal waveforms for efficient pulse transmission/reception, suitable for use in UWB applications. Comparative results of UWB characteristics of the novel antenna with other designs is also presented which shows that novel design has better UWB characteristics than the previously reported designs, which additionally proves the distinctive capability of the proposed antenna for use in UWB communications.

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