

Ultra-Wideband Log Periodic Dipole Antenna (LPDA) for Wireless Communication Applications

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Abstract

This paper proposes a printed log-periodic dipole antenna (LPDA) for ultra wide bandwidth (UWB) applications. The antenna comprises of cascading four U shaped elements of different line lengths with balun circuit to improve the antenna impedance matching. The proposed antenna dimensions are $50 \times 50 \text{ mm}^2$ with FR4 substrate thickness 0.8 mm. Full-wave EM solver HFSS (High Frequency Structure Simulator) is used for modeling the proposed antenna. The pulse distortion is verified by the measured the proposed antenna performance with virtually steady group delay. The simulation and experimental results show that the proposed antenna exhibits good impedance matching, stable radiation patterns throughout the whole operating frequency bands, acceptable gain and stable group delay over the entire operating band. An UWB extended from 1.85 GHz to 11 GHz is obtained, and the average antenna gain is about 5.5 dBi over the operating band with peak gain around 6.5 dBi and 70% average radiation efficiency.

Keywords

High Frequency Structure Simulation (HFSS), Dipole Antenna, Log Periodic, Coplanar Waveguide (CPW), Ultra Wideband (UWB), Radiation Pattern, Radiation Efficiency, Group Delay

1. Introduction

Latterly, much progress has been made in ultra-wideband (UWB) applications with high data rate communications in short distances with low fabrication cost. UWB system antennas demand serious challenges to achieve wide impedance bandwidth, compact size, high gain, linear group delay, stable radiation patterns

[1] [2] [3] [4] and to meet the demand for mobile, wireless communication, personal applications, the industrial medical ISM-band 2.4 GHz, LTE 2.1 GHz, the IEEE 802.11a bands (5.15 - 5.35 GHz, 5.725 - 5.825 GHz) HIPERLAN/2 bands (5.15 - 5.35 GHz, 5.470 - 5.725 GHz) which can interfere with the UWB communication systems [5] [6]. In addition, FCC in 2002 released the UWB protocol that covers the frequency range from 3.1 - 10.6 GHz [1]. UWB antennas used planar microwave circuitry have generated attractive radiating structures with high gain, low weight, reliability, ease of manufacturing and integration such as the Vivaldi antennas [7] [8], and the tapered slot antenna [9]. The most suitable solution at microwave frequencies appears to be the printed planar log-periodic dipole (LPDA) [5] [6]. LPDAs have a lot of advantages, such as directive radiation pattern, linear polarization and low cross polarization ratio over a wide frequency range [5]. At the beginning, coaxial cable is used for feeding the printed LPDAs at the radio and the TV frequency bands; however, it was found that the performance became worse when frequency increases. LPDA is UWB with the multiple resonance property; its bandwidth can be enhanced by increasing the number of the dipole elements [8] [9] [10] [11]. Balanced structure, CPW fed antennas are very good candidates since the feed lines and the slots are on the same side of the substrate. There are many researches done to design LPDA as shown in **Table 1** to resonate at different wireless communications or for UWB applications. **Table 1** shows that most of published papers for LPDA are not compact and their size are near from wavelength.

In this paper a new proposed ultra wideband antenna, is presented which consists of a combined structure of different lengths of printed U-shaped LPDA fed by CPW and balun circuit to improve the impedance matching. These bands are used for different wireless communications applications and also for UWB applications. The USLPDA as shown in **Figure 1** has been designed with 3D electromagnetic simulation HFSS ver. 14. The compact antenna dimensions are $50 \times 50 \times 0.8 \text{ mm}^3$ when printed on a FR4 dielectric substrate. The proposed USLPDA antenna introduces USUWB with the multiple resonant property and compact size compared to earlier designs where ultra wide bandwidth was realized using a rectangular slot [9].

USLPDA bandwidth can be enhanced by increasing the number of the

Table 1. Comparison of proposed antenna with other antennas (all dimensions in mm).

Ref.	$L \times W \text{ mm}^2$	Sub. Thickness	Diel. Properties	BW GHz
[6]	91×57	1.578	$\epsilon_r = 2.2, \tan \delta = 0.0009$	2.75 - 11
[7]	29×26	1.588	$\epsilon_r = 4, \tan \delta = 0.02$	1.8 - 3.75
[8]	45×60	1.5	$\epsilon_r = 4.4, \tan \delta = 0.02$	5 to 40
[9]	70×40	0.51	$\epsilon_r = 2.5, \tan \delta = 0.0002$	4 to 18
[10]	238×112	1.58	$\epsilon_r = 2.2, \tan \delta = 0.0001$	2 to 18
Our	50×50	0.8	$\epsilon_r = 4.6, \tan \delta = 0.02$	1.85 to 11

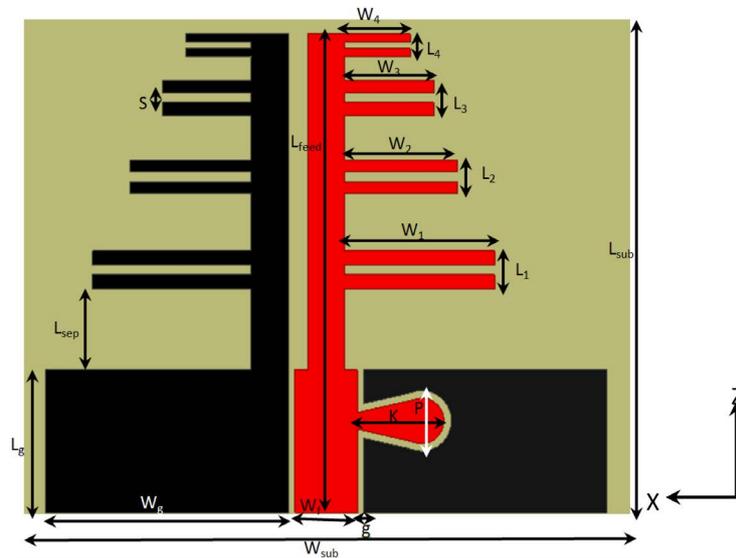


Figure 1. Layout of the proposed log periodic dipole antenna (US-LPDA).

U-shaped dipole elements or stubs [10]-[15]. The -10 dB bandwidth of this antenna extends from 1.85 to 11 GHz which is wide enough to cover the FCC approved UWB in addition to wireless communications. The antenna exhibits good performance and can operate at wireless applications. The antenna structure with design, parametric study and the evolution of the proposed the antenna are presented in Section 2. In Section 3, proposed antenna is analyzed in terms of reflection coefficient, surface current distribution, group delay and antenna gain. The fabricated antenna is evaluated based on the measurement of $|S_{11}|$ and radiation pattern in Section 4. Finally, Section 5 concludes the proposed work.

2. Antenna Geometry and Design

The proposed antenna geometry is shown in **Figure 1**; the antenna consists of four different lengths of LPDA with U-shaped stubs. The lengths and spacing of the elements of a log-periodic antenna increase logarithmically from one end to the other. The design of the LPDA is used where a wide range of frequencies is needed while still having moderate gain and directionality. The initial design is validated and optimized by simulating the proposed antenna using HFSS. The proposed antenna is built on a low-cost FR4 substrate with substrate thickness 0.8 mm, dielectric constant $\epsilon_r = 4.6$, and loss tangent $\tan \delta = 0.02$ as shown in **Figure 1**. The antenna is fed by a 50Ω transmission line, which can be easily integrated with other microwave circuits printed on the same substrate. For designing procedure, a number of trial steps are needed, the scale-factor τ , spacing factor δ , and the number of the dipole elements N should be determined. Second, the length of the longest arm, which responses to the lowest resonance frequency f_r , should be computed by following Equations (1) to (6) [1]. The dimensions of the traditional antenna elements can be determined with:

$$\frac{W_{i-1}}{W_i} = \tau \tag{1}$$

$$\delta = \frac{L_{isep}}{4W_i} \tag{2}$$

$$W_i = \frac{\lambda_{1,eff}}{4} \tag{3}$$

$$N = 1 - (\ln B_s / \ln \tau) \tag{4}$$

$$B_a = 1.1 + 30.7\delta(1 - \tau) \tag{5}$$

$$B_s = B_a B_o \tag{6}$$

where $\lambda_{1,eff}$, B_o , N , $int i$ are the longest effective operating wavelength, the operating frequency, number of elements, and i is an integer that varies from 2 to 5, respectively. The lengths of the first, second, third and fourth dipoles should be scaled due to the effective dielectric constant of antenna substrate. Based on the traditional design procedure, we propose a new USLPDA, in which the scale factor and the spacing factor are different compared to the traditional equations. As shown in **Figure 1**, by cascading the straight line LPMA, UWB antenna is realized, where the red elements are the radiator surface of the substrate and the black elements are the ground plane surface of the substrate. Four U-shaped stubs are added in each element to add extra four resonant frequencies when their lengths equal to quarter wavelength. To improve the impedance matching the balun circuit with suitable dimensions is used as shown in **Figure 2**.

3. Simulated Results

The antennas are modeled and analyzed by using HFSS electromagnetic software. The simulated $|S_{11}|$ for the antenna design steps are depicted in **Figure 3**. However, the overall impedance bandwidth for the proposed U-shaped log periodic dipole model is much wider.

The introduced design started by conventional dipole with length 45 mm as shown in **Figure 2(a)** which resonates at 2.4 GHz as shown by dashed black line in **Figure 3**. The second step of design is adding balun circuit to improve the antenna bandwidth as shown in **Figure 2(b)** and the corresponding result is shown as solid red line in **Figure 3**. First US-LPDA is added in the third step of design as shown in **Figure 2(c)**, this adds two extra resonant frequencies as

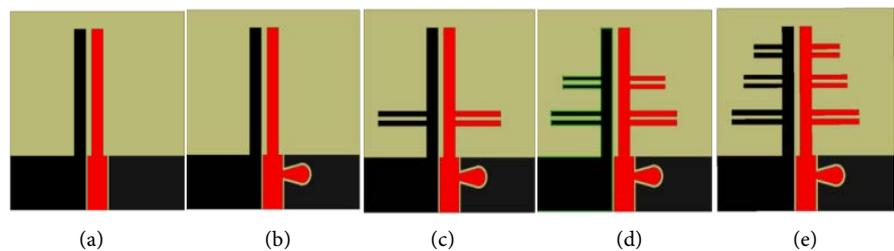


Figure 2. From (a) to (e) evolution of the design steps of the proposed US-LPDA.

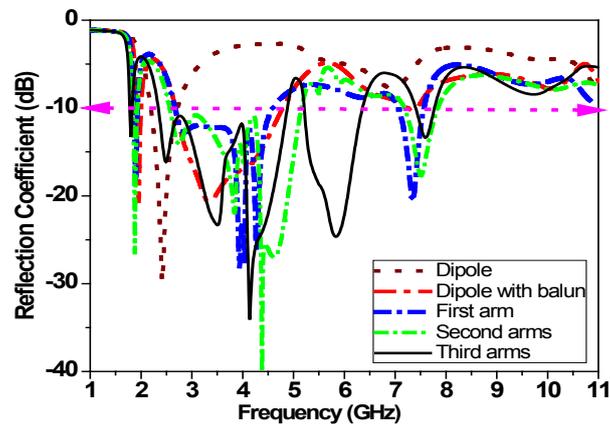


Figure 3. Design procedures of the USLPDA antenna.

shown as blue dashed line in **Figure 3**. Continuing the design by adding the second U-shaped element, as shown in **Figure 2(d)**, the response is shown as green line in **Figure 3**. In addition, a third element is added as shown in **Figure 2(e)** and its response is shown in **Figure 3** as brown dashed line. Final design as shown in **Figure 1** and the corresponding $|S_{11}|$ results are shown in **Figure 4**. There are two orientations of the elements arrangement with the same lengths either from small size element length to large size element or vice versa as shown in **Figure 4(a)**. The reflection coefficients $|S_{11}|$ of both orientations are shown in **Figure 4(b)**. The orientation from small to large size elements gives lower antenna resonant frequency at 1.5 GHz with poor impedance matching, while the other orientation from large to small size elements gives resonant frequency at 1.85 GHz and good impedance matching.

The effects of each arm of the proposed antenna are also studied and the simulated reflection coefficient of varied each arm and kept the other arms fixed are shown in **Figure 5**.

Figure 5 Shows the effect of varies L_1 , L_2 , L_3 and L_4 and the corresponding results are shown in **Figure 5(a)** to **Figure 5(d)**. Optimized antenna dimensions are shown in **Table 2**. Simulated current density distributions of the USLPDA with four elements are shown in **Figure 6** at different resonant frequencies take place at 1.85 GHz, 2.45 GHz, 3.5 GHz, 5.5 GHz, 7.5 GHz and 10 GHz. The current distribution of the proposed antenna is studied to verify the operation of the USLPDA. The largest element fundamental resonant frequency of the multi arms is 1.75 GHz as shown in **Figure 6(a)**. The highest magnitude of current (red) is related to the corresponding element of radiation.

Group Delay is an important factor in communication systems especially ultra-wideband for example medical applications systems, security systems and satellite communication systems which are used for transmitting wideband data, because the distortion causes retraction of the S/N ratio [16]-[22]. Flat and consistent GD with frequency is important. To avoid occurring of distortion it is recommended that the spectrum is treated in the same manner, over the proposed bandwidth of frequencies. When GD ripples are large they may cause

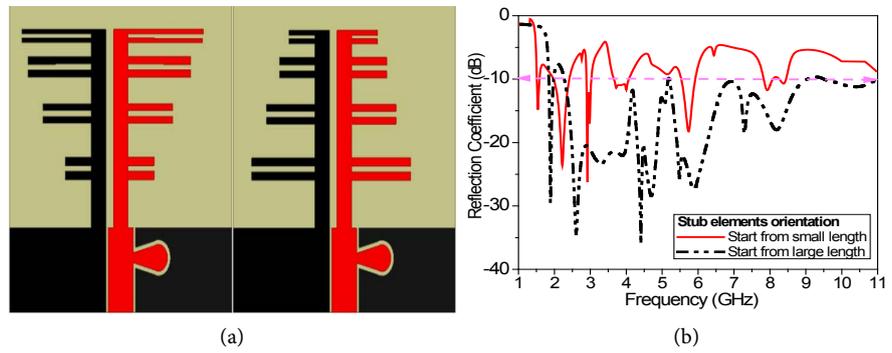


Figure 4. (a) Two different orientations of USLPDA and (b) the corresponding reflection coefficient $|S_{11}|$.

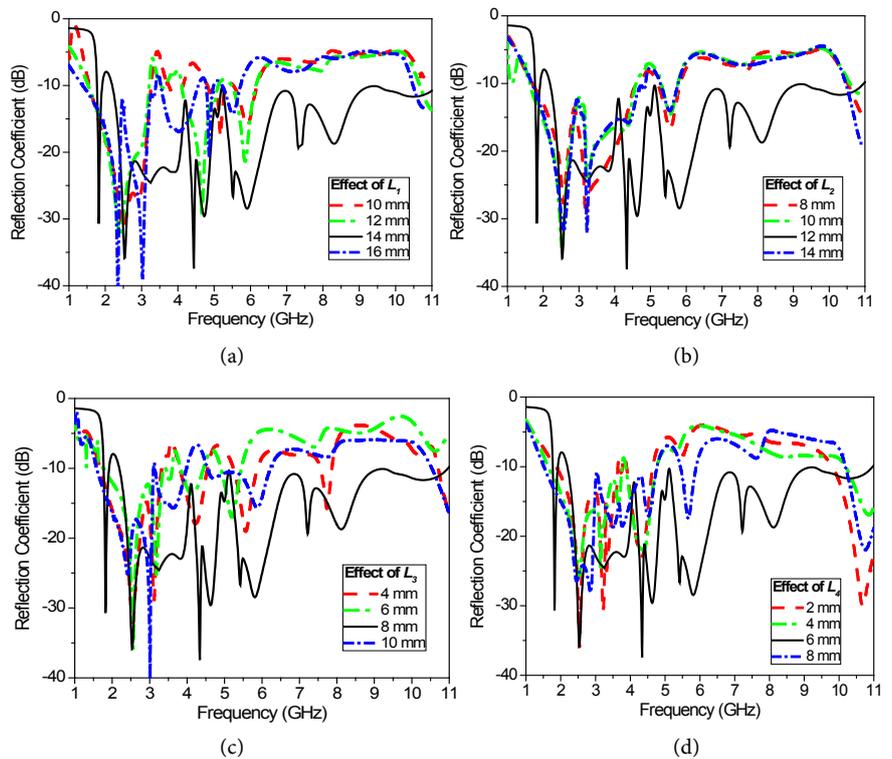


Figure 5. (a) to (d) Simulated S-parameters of proposed LPDA with varies arms L_1 , L_2 , L_3 and L_p respectively.

Table 2. Dimensions of the proposed antenna (dimensions in mm).

L_{sub}	L_g	W_{sub}	W_g	W_1	W_2	W_3	S	g	W_4
50	13.5	50	24	15.3	11.7	8.5	0.9	0.6	6
L_{sep}	L_4	L_{feed}	L_3	L_1	L_2	W_f	K	P	d
7.6	2.1	45	2.8	3.6	3	6	8.5	4.5	1000

unsatisfactory distortion in the signal of a transmitting radio system. So, in radio system design there is usually a specification for how much a GD that may be accepted. In nonlinear systems nonlinear distortion happens since the magnitude of

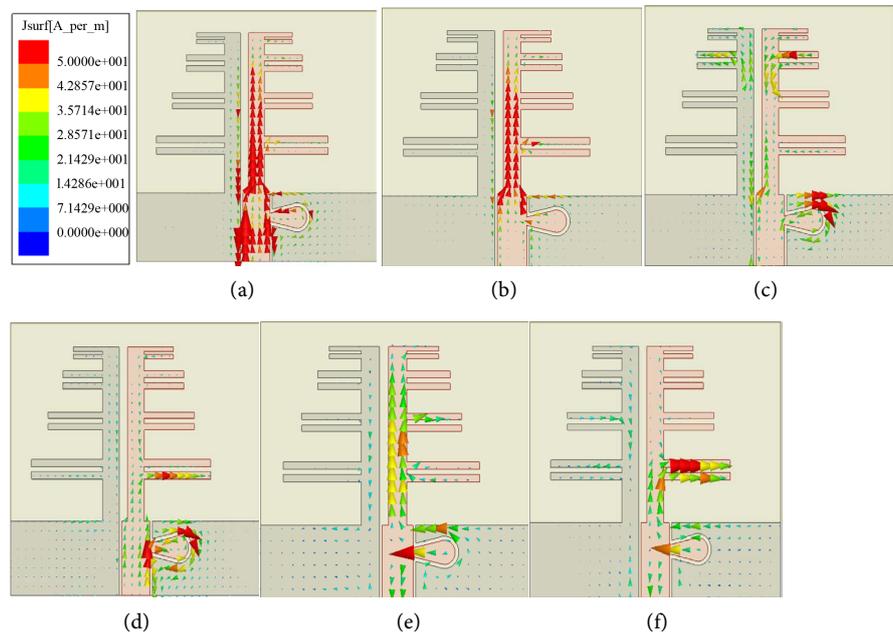


Figure 6. From (a) to (f) surface current densities for the USLPDA at 1.85, 2.45, 3.5, 5.5, 7.5 and 10 GHz, respectively.

frequency response is not constant and the phase of frequency response is non-linear. By using GD the phase distortion could be measured, the phase characteristics must have a linear slope so that the ratio is constant for all frequencies and this represents a constant GD [21]. To measure the GD between two antennas with spacing $d = 1$ m, the usual practice is to derive Q/ω from $|S_{21}|$ phase. However, it is desirable the same antenna be used for transition and receiving antenna. High GD variations, due to the steep phase shift over frequency, may cause unsatisfactory distortion in the signal. **Figure 7** illustrates the simulated GD, and it can be noticed that the average group delay is about 1.5×10^{-9} second.

4. Implementation and Measured Results

Prototype of the proposed antenna is fabricated on FR4 substrate by using photolithographic technique, as shown in **Figure 8** and performance parameters are measured. The simulated and measured input reflection coefficient of the antennas is in very good agreement, as shown in **Figure 8(b)**. Impedance -10 dB bandwidth of the proposed dipole antenna extended from 1.85 GHz to 11 GHz to cover most of wireless applications and FCC UWB regulation. The measurements were carried out by using a Rohde & Schwarz ZVA67 vector network analyzer operating from 50 MHz to 67 GHz. The comparisons between measured and simulated results of antenna gain and radiation efficiency are also studied as shown in **Figure 9**. The USLPDA antenna achieves simulated average gain 5.5 dBi and the peak realized gain around 6.5 dBi at 2.7 GHz as shown in **Figure 9(a)**. The measured results show very good agreement with simulated results and about ± 3 dBi difference on average over the operating band. Wheeler

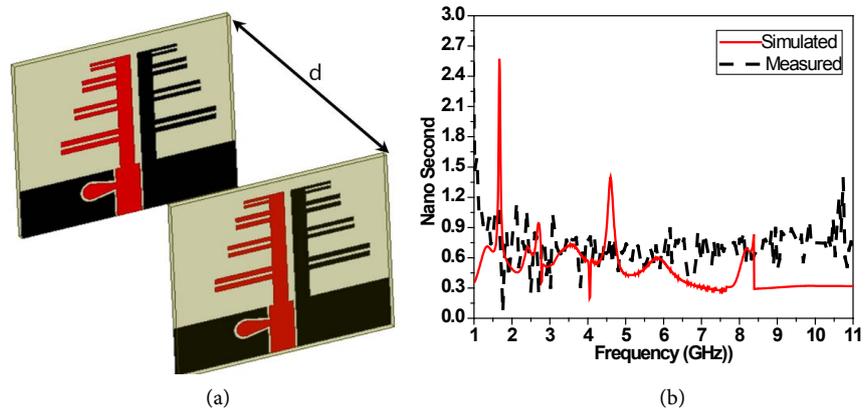


Figure 7. (a) GD Simulated structures and (b) comparison between measured and simulated GD of USLPDA.

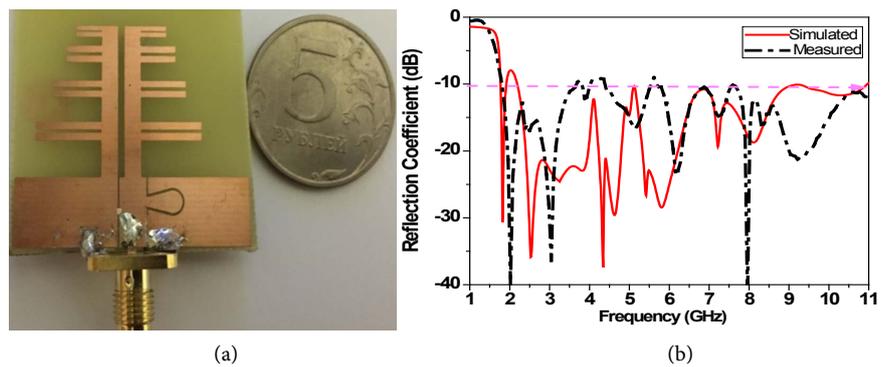


Figure 8. (a) Fabricated USLPDA antenna and (b) $|S_{11}|$ comparison between simulated and measured results.

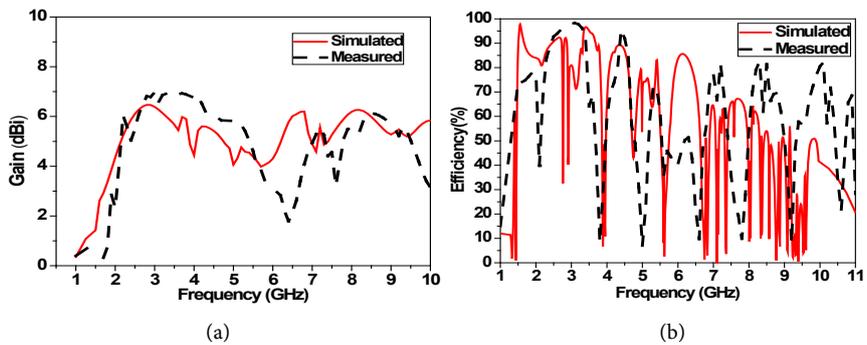
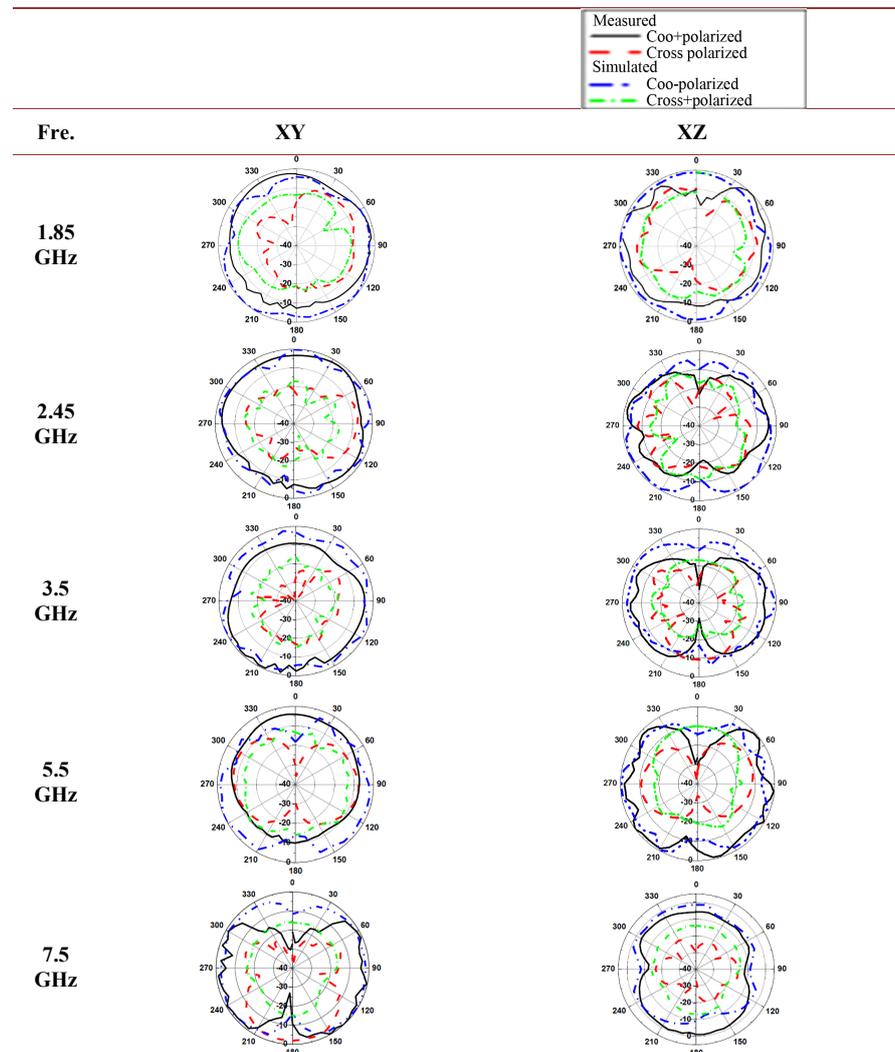


Figure 9. Comparison between simulated and measured results (a) gain and (b) radiation efficiency of USLPDA.

cap method [23] [24] can be used to calculate so that the antenna radiation efficiency was simulated for the proposed antenna by using. The average radiation efficiency is around 70% over the operating bands as shown in **Figure 9(b)**. Then the measured result of the radiation efficiency is done by using horn antenna to complete the proposed antenna radiation efficiency measurement as shown in **Figure 9(b)**. Simulation and measured results for the two dimensional radiation patterns of two main planes (XZ and XY) are depicted in **Table 3** at

Table 3. Simulated and measured results of the proposed antenna radiation patterns in both XY and XZ planes at different frequencies. 1.85 GHz, 2.45 GHz, 3.5 GHz, 5.5 GHz and 7.5 GHz.



different resonant frequencies 1.85 GHz, 2.45 GHz, 3.5 GHz, 5.5 GHz, and 7.5 GHz, respectively. In the proposed antenna, the radiator and the ground plane are contributing to radiation. Omnidirectional radiation pattern is an important requirement for UWB applications. At lower frequencies of operation, the pattern resembles a conventional dipole antenna, but at higher end of the UWB spectrum some ripples are observed which are attributed to higher order modes. Some discrepancies are observed at higher frequency band spectrum which arises due to measurement setup. The simulated and measured results suggest that the proposed antenna shows satisfactory omnidirectional radiation characteristics throughout the UWB band.

5. Conclusion

A new ultra-wideband antenna consists of U shaped log-periodic dipole antenna

(USLPDA) has been proposed in this paper. The dipole is cascaded with four-U shaped elements to create an ultra-wideband extended from 1.85 GHz to 11 GHz. The proposed technique not only results in miniaturization of the antenna but also provides very stable radiation patterns throughout the whole frequency band. The proposed antenna can be easily fabricated on any commercially available substrates using the present design guidelines. This antenna has an average gain of 5.5 dBi and 70% average radiation efficiency over the operating resonant frequencies. These features make the proposed antenna suitable for different wireless communication systems as well as UWB applications.

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