Design and Analysis of Quad-Band Notch Characteristics UWB Antenna Using SLR Circuits

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Abstract—In this paper, a quad-band notch characteristics ultra-wideband (UWB) antenna for Wi-MAX, L-WLAN, U-WLAN, and C-band applications is presented. The initial UWB antenna bandwidth is achieved in the 2 to 12.5 GHz frequency band by using the partial ground method. Spiral lossy resonator (SLR) slots are loaded into the UWB ground structure to achieve quad-band notch characteristics. Each SLRS circuit is accountable for a single notch characteristic by losing EM power at the notch frequency. A quad-band notch is accomplished in this antenna for WiMAX (3.24 to 3.56 GHz), L-WLAN (4.76 to 5.34 GHz), U-WLAN (5.58 to 5.91 GHz), and C-band (7.37 to 7.71 GHz) by loading four SLR slots circuits into the UWB antenna. The proposed antenna is engraved on a Rogers RO4003C (3.55) substrate having an overall volume of $50 * 40 * 1.524 \, \text{mm}^3$. The proposed antenna's performance has been verified through simulation and experiments.

1. INTRODUCTION

Ultra-wideband (UWB) technology has provided very low energy levels for short-range, high-information spread capabilities with a massive bandwidth, often more than 500 MHz, since the Federal Communications Commission (FCC) opened the 3.1–10.6 GHz spectrum for commercial purposes. Wireless location systems, sensor networks, biomedical imaging, and high-data short-range communications are just a few of the areas where UWB may be used [1, 2]. As a result, in recent years, their design challenge has become a major study area. UWB antenna designers must balance high impedance bandwidth, radiation-pattern stability, compactness, and cheap manufacturing costs in their designs [3–5].

Aside from these worries, the problem of electromagnetic interference (EMI) created by existing narrowband communication technologies like WiMAX (3.3–3.8 GHz), WLAN (5.15–5.85 GHz), and satellite downlink band (7.25–7.75 GHz) is a major source of concern [6–9]. It is difficult to develop antennas with desirable qualities like improved impedance matching, consistent radiations, small size, and low cost. Because of their light weight, flat design, and simplicity of integration with other electrical components, patch antennas are better candidates for UWB applications. External band-stop filters are used to obtain the appropriate band rejection, which adds to the system's complexity and bulk. As a result, designers have resorted to incorporating parasitic slots or strips of various forms in the radiating element or ground plane structure of antenna systems in order to maintain the antenna compact. Furthermore, many UWB applications necessitate the use of mutually non-interacting notch bands [3, 5, 8–11].

As indicated in Table 2, there have been a number of methods for constructing numerous rejected bands for UWB applications. In [1], a quad-band UWB antenna uses a loading L-shape slot, complimentary split ring resonator, and C-shape slots. A tunable UWB band-notched antenna with loading asymmetric T-shaped open-ended stubs and J-shaped open-ended stubs is reported in [12]. A

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UWB antenna with three rectangular notches using an inserting electromagnetic bandgap (EBG) and split-ring resonators (SRRs) is reported in [3]. By inserting an elliptical split ring resonator (ESRR), rectangular split ring resonators notch antennas are designed reported in [13–15]. The described method of etching slots in radiation elements may have a major influence on the existing distribution of passband frequencies, potentially changing passband radiation patterns. The effectiveness of the used approaches determines the selectivity of rejection bands. In this work, spiral lossy resonator (SLR) slots are loaded into a UWB ground structure to obtain quad-band notch characteristics. Each SLR slot controls a single notch frequency by controlling the total length of the SLR slot; therefore, we can simply adjust notch frequency by managing the total length of SLR slots to achieve multiple notch characteristics. These approaches can provide extremely efficient notch band designs.

A quad-band notch characteristics UWB antenna for Wi-MAX, L-WLAN, U-WLAN, and C-band applications is discussed in this paper. The system is designed using an EM full-wave commercial software CST Studio Suite. A detailed analysis of antenna designs such as UWB and UWB with notched antenna, as well as other design characteristics, is presented. A prototype is fabricated to verify the simulated results. The results of the simulation and measurement are compared and found to be in good agreement. The paper's novelty quad band characteristics comes by loading SLR slots at bottom of the antenna. The structure of the paper is summarized below. The original design is described in Section 2, whereas Section 3 depicts design stages of the UWB antenna. The construction and operation of the notched UWB antenna are addressed in Section 4. Finally, Section 5 reveals the paper's conclusion.

2. PROPOSED ANTENNA DESIGN CONFIGURATION

The proposed UWB notch antenna's top and bottom part configurations are shown in Figures 1(a) and (b). The design comprises a partial ground antenna along with quad notch slots (SLR slots) at bottom part of the antenna as represented in Figures 2(a), (b), (c), (d). The volume of the proposed antenna designed on Rogers RO4003C (3.55) is $50 \times 40 \times 1.524 \, \text{mm}^3$. The proposed antenna has been designed and simulated by CST Studio Suite, and its designed parameters are shown in Table 1.
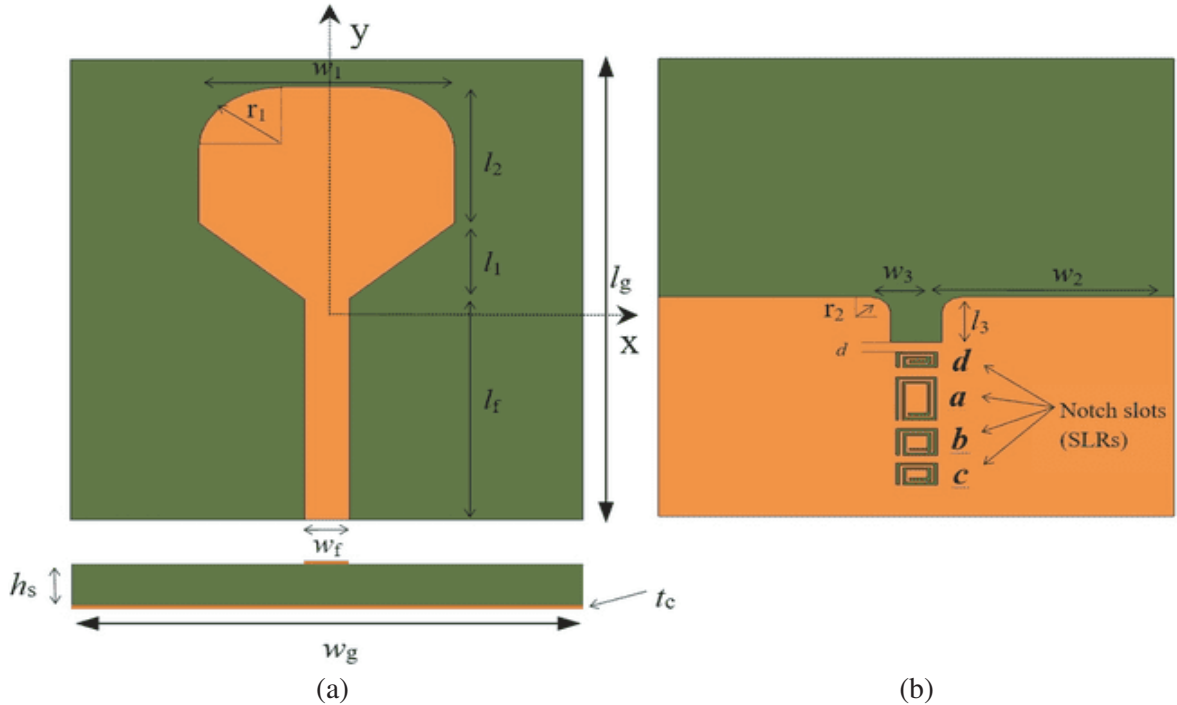

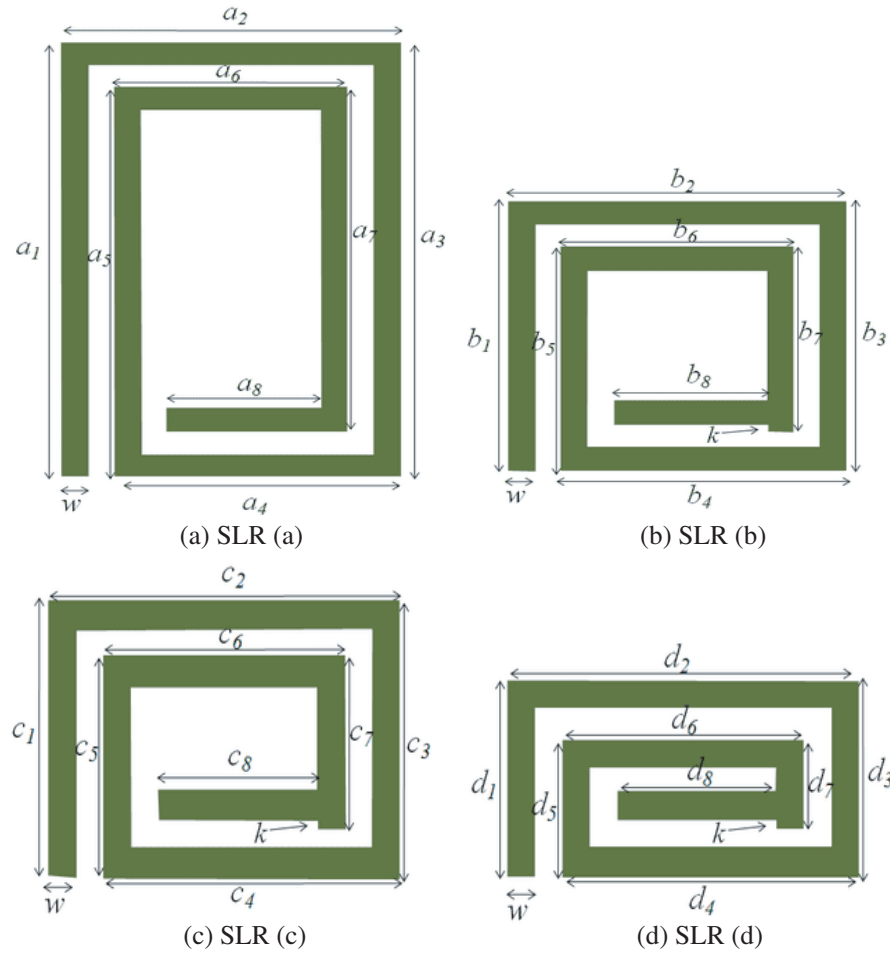**Figure 1.** Geometrical structure of the proposed antenna. (a) Top view. (b) Bottom view.

Figure 2. SLR slots for (a) band-1, (b) band-2, (c) band-3, and (d) band-4.

3. DESIGN PROCESS OF UWB ANTENNA

As illustrated in Figure 3, the UWB antenna design process is separated into four parts, labeled Ant.1 through Ant.4. Initially, a conventional rectangular antenna with a microstrip feed 50-ohm impedance
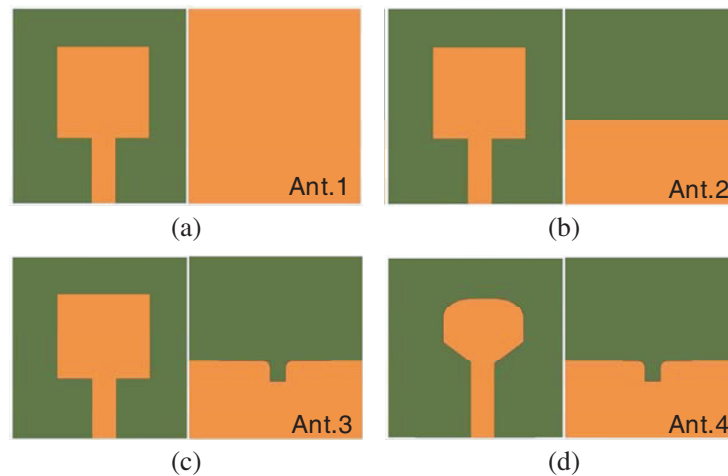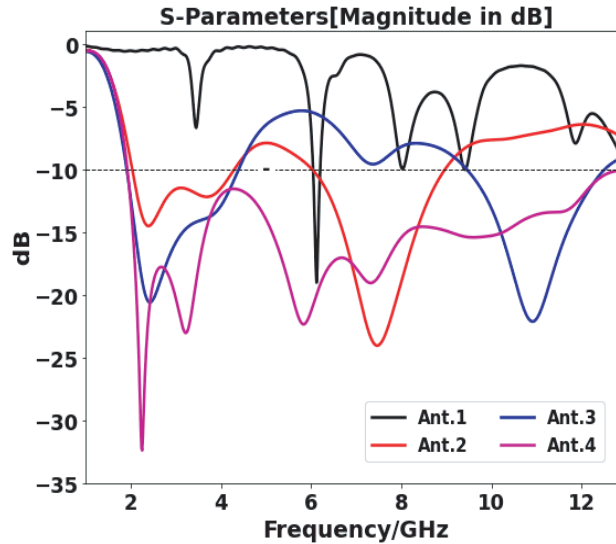

Figure 3. Design steps of UWB antenna. (a) Ant.1. (b) Ant.2. (c) Ant.3. (d) Ant.4.

Table 1. The UWB notch antenna designed parameters of proposed antenna.

Parameters	Values (mm)	Parameters	Values (mm)	Parameters	Values (mm)
w_g	40	w_3	4	w_f	3.5
l_g	50	l_1	8.25	l_f	24
w_1	20	l_2	14.75	r_1	6.66
w_2	18	l_3	5	r_2	1.66
d	1.08	w	0.25	a_1	4.45
a_2	2.70	a_3	4.20	a_4	2.2
a_5	3.70	a_6	1.70	a_7	3.2
a_8	1.45	b_1	2.65	b_2	2.7
b_3	2.4	b_4	1.45	b_5	1.9
b_6	1.7	b_7	1.40	b_8	1.45
d_5	0.7	d_6	1.7	d_7	0.2
d_8	1.45	k	0.25	h_s	1.52
L_{ea}	23.60	L_{eb}	15.90	L_{ec}	14.65
L_{ed}	11.85	h_s	1.524	t_c	0.035
c_1	2.15	c_2	2.7	c_3	1.9
c_4	2.2	c_5	1.4	c_6	1.7
c_7	0.9	c_8	1.45	d_1	1.45
d_2	2.7	d_3	1.2	d_4	2.2

line is designed at 6 GHz, and its designed parameters are calculated by transmission line method (TLM) [16]. The simulated scattering parameters of antennas are shown in Figure 4. The resonance frequency of Ant.1 is about 6.2 GHz. Ant.1 is modified by partial ground to enhance antenna bandwidth as shown in Figure 4 for Ant.2. In Ant.3, a rectangular slot with tapper corners is etched out from antenna ground to achieve better impedance matching with feed line. To further improve the bandwidth,

Figure 4. S_{11} plots of UWB antenna Ant.1, Ant.2, Ant.3, and Ant.4.

the corners of the radiating section are truncated as shown in Ant.4, and its corresponding S_{11} plot is shown in Figure 4. Finally, UWB characteristics are achieved by a combination of partial ground, rectangular center ground slot, and truncated corners of the radiating part. The achieved impedance bandwidth of UWB antenna at ($S_{11} < -10$ dB) is from 1.9 GHz to 13 GHz.

4. DESIGN PROCESS OF UWB QUAD-BAND NOTCH ANTENNA

As illustrated in Figure 5, the design procedure for a UWB antenna with a quad-band notched is divided into four sections, labeled Ant.5 to Ant.8.
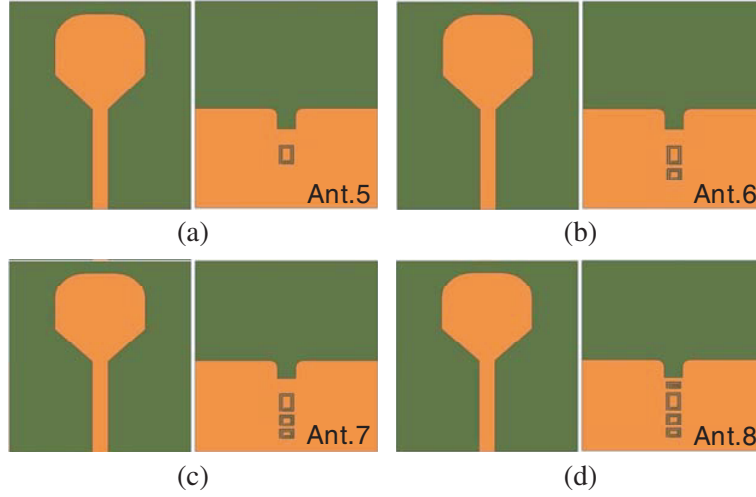

(a)

(b)

(c)

(d)

Figure 5. Design steps of UWB notch antenna. (a) Ant.5, (b) Ant.6, (c) Ant.7, and (d) Ant.8.

4.1. Working of UWB Quad-Band Notch Antenna

By inserting SLR slots in ground with different equivalent lengths, the notched characteristic for specific band is achieved. By controlling equivalent length of SLR slots, the band notch characteristics can be adjusted. The notch band frequency (f_n) of SLR slot is calculated analytically as given equation [14]

$$f_n = \frac{c}{2 * L_e * \sqrt{\varepsilon_r}} \tag{1}$$

The total electrical length (L_e) of the SLR slot is determined analytically as

$$L_e = \frac{\lambda_n}{2} = \frac{c}{2 * f_n \sqrt{\varepsilon_r}} \tag{2}$$

where ε_r is the dielectric constant of dielectric material, and λ_n is the wavelength at notch frequency.

The total electrical length of the first notch can be calculated analytically at $f_{na} = 3.40$ GHz (resonance notch SLR slot frequency).

For WiMAX band (3.24 to 3.56 GHz) rejection

$$L_{ea} = \frac{\lambda_{na}}{2} = \frac{c}{2 * f_{na} \sqrt{\varepsilon_r}} = \frac{3 * 10^8}{2 * 3.40 * 10^9 * \sqrt{3.55}} = 23.41 \text{ mm (Analytically)}$$

The simulated total electrical length of SLR slot for first notch is given by Figure 2(a)

$$L_{ea} = a_1 + a_2 + a_3 + a_4 + a_5 + a_6 + a_7 + a_8 = 23.60 \text{ mm (Simulated)}$$

At the first notch resonance frequency, Figure 6(a) depicts the antenna's surface current distribution ($f_{na} = 3.40$ GHz). The surface current is maximum in SLR (a) slot. At notch frequency, the maximum input power is delivered to SLR slot instead of radiation part of antenna. At this notch frequency, the

SLR (s) slot produces a strong resonance near slots length and achieves good band notch characteristics for WiMAX band rejection. The notch resonance frequency can be controlled by varying the total equivalent length of SLR slot as shown in VSWR parametric study of Figure 7. Similarly, L-WLAN, U-WLAN, and C band can be reject from UWB frequency using inserting SLR (b), SLR (c), and SLR (d) slots in antenna, and its surface current distribution and VSWR parametric study plots are shown in Figures 6(b), (c), and (d) and Figures 8, 9, and 10, respectively. Figure 12 depicts the proposed antenna's radiation efficiency; it demonstrates that radiation efficiencies are the lowest at notch frequencies, implying that most power is lost through SLR slots, and that radiation efficiency is the highest outside notched bands. Analytically, the notion of SLR slots has been proven; the analytical total electrical lengths are computed without taking the effects of fringing into account; however, in simulation, the fringing effect adds extra lengths.
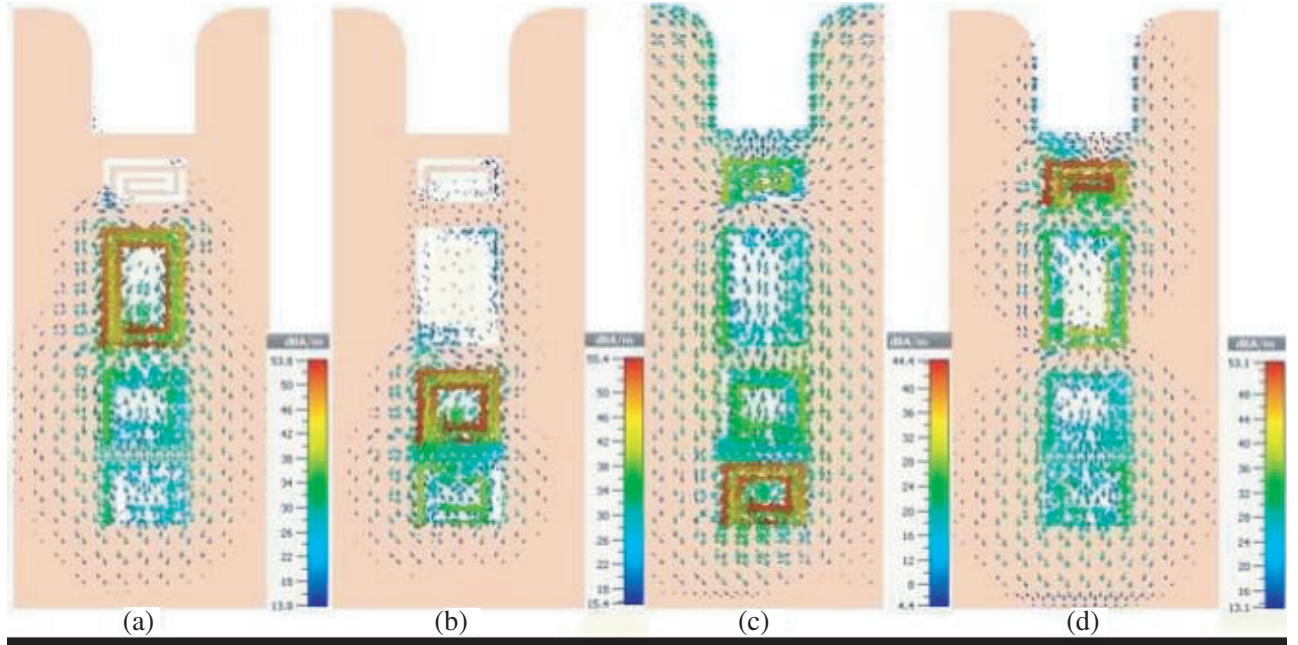

Figure 6. Surface current at notch frequency. (a) Ant.5. (b) Ant.6. (c) Ant.7. (d) Ant.8.
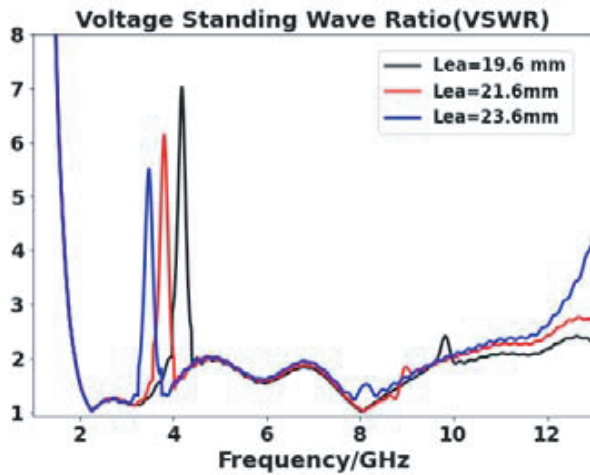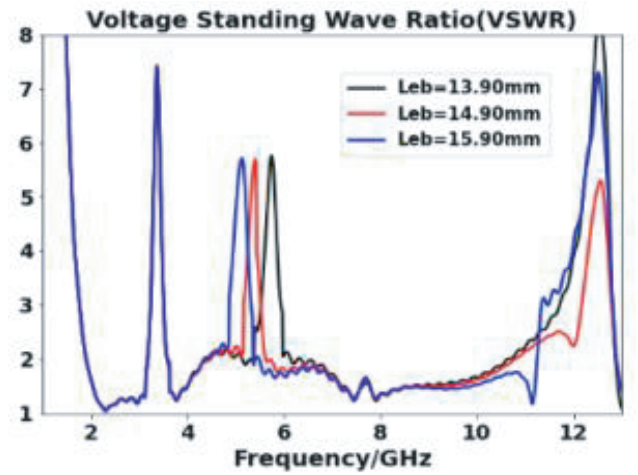

Figure 7. VSWR plot of parametric study for SLR (a).

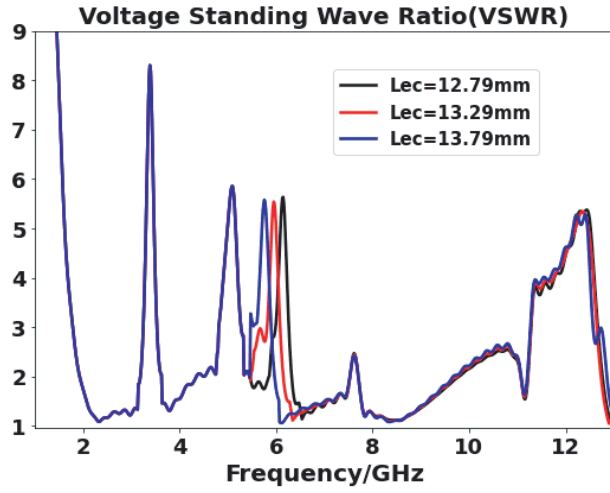**Figure 8.** VSWR plot of parametric study for SLR (b).

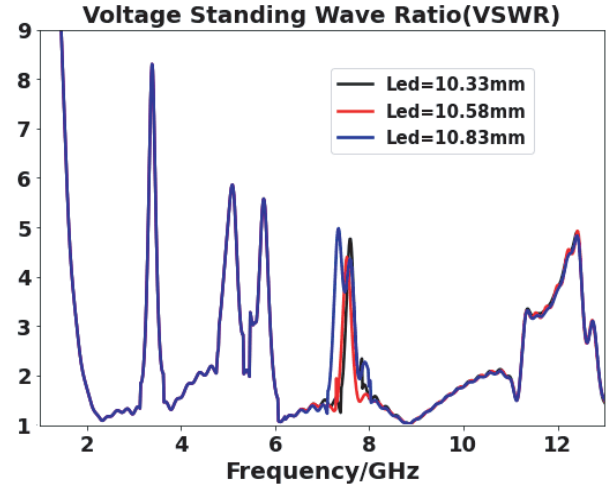**Figure 9.** VSWR plot of parametric study for SLR (c).

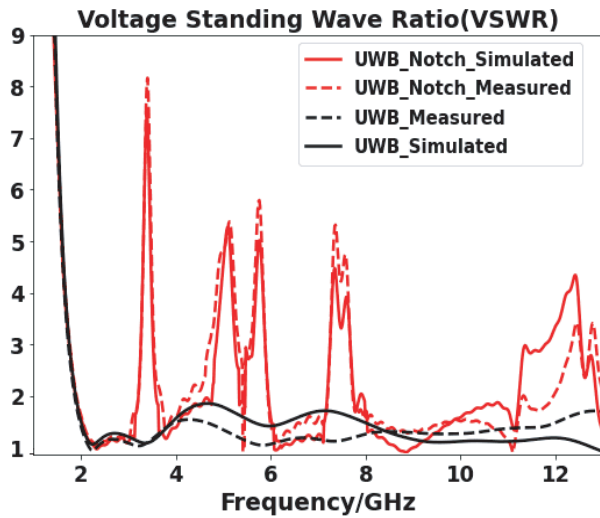**Figure 10.** VSWR plot of parametric study for SLR (d).

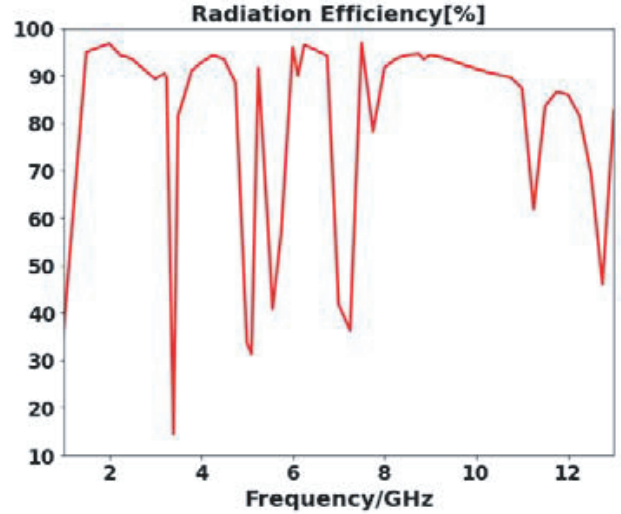**Figure 11.** Simulated and measured VSWR plots.

Figure 12. Simulated radiation efficiency plot.

For L-WLAN band (4.76 to 5.34 GHz) rejection, at $f_{nb} = 5.05$ GHz

$$L_{eb} = \frac{\lambda_{nb}}{2} = \frac{c}{2 * f_{nb}\sqrt{\varepsilon_r}} = \frac{3 * 10^8}{2 * 5.05 * 10^9 * \sqrt{3.55}} = 15.76 \text{ mm (Analytically)}$$

The simulated total electrical length of SLR slot for the first notch is given by Figure 2(b)

$$L_{eb} = b_1 + b_2 + b_3 + b_4 + b_5 + b_6 + b_7 + b_8 + k = 15.90 \text{ mm (Simulated)}$$

For U-WLAN band (5.58 to 5.91 GHz) rejection, at $f_{nc} = 5.74$ GHz

$$L_{ec} = \frac{\lambda_{nc}}{2} = \frac{c}{2 * f_{nc}\sqrt{\varepsilon_r}} = \frac{3 * 10^8}{2 * 5.74 * 10^9 * \sqrt{3.55}} = 14.08 \text{ mm (Analytically)}$$

The simulated total electrical length of SLR slot for the first notch is given by Figure 2(c)

$$L_{ec} = c_1 + c_2 + c_3 + c_4 + c_5 + c_6 + c_7 + c_8 + k = 14.65 \text{ mm (Simulated)}$$
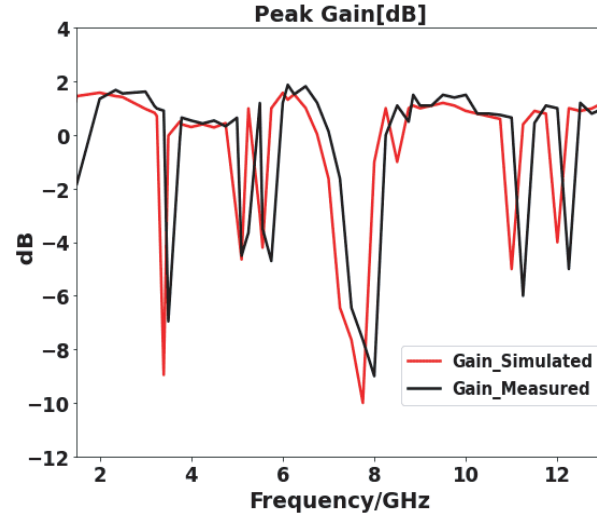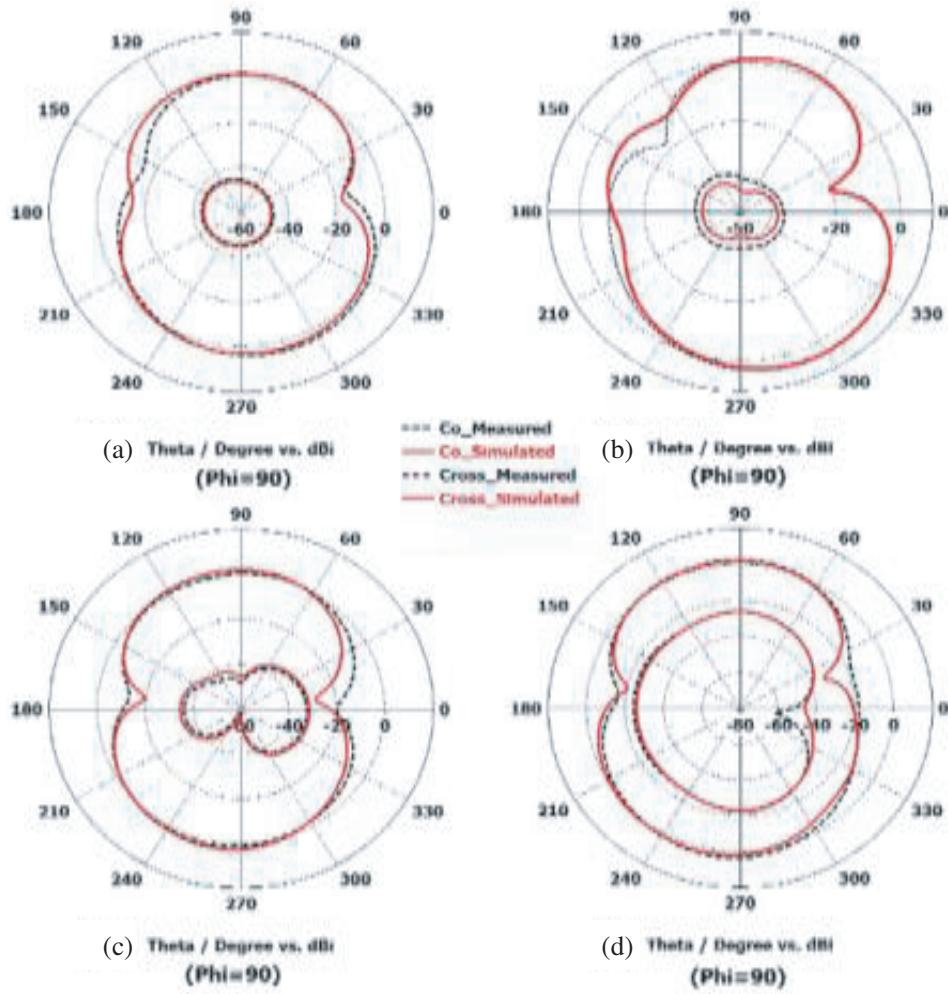
Figure 13. Simulated and measured peak gains.

Figure 14. Co and Cross polarization plots. (a) 2.6 GHz, (b) 4 GHz, (c) 5.5 GHz and, (d) 6.57 GHz.

For C band (7.37 to 7.71 GHz) rejection, at $f_{nd} = 7.54\,\text{GHz}$

$$L_{ed} = \frac{\lambda_{nd}}{2} = \frac{c}{2 * f_{nc}\sqrt{\varepsilon_r}} = \frac{3 * 10^8}{2 * 7.54 * 10^9 * \sqrt{3.55}} = 10.55\,\text{mm (Analytically)}$$

The simulated total electrical length of SLR slot for the first notch is given by Figure 2(d)

$$L_{ed} = d_1 + d_2 + d_3 + d_4 + d_5 + d_6 + d_7 + d_8 + k = 11.85\,\text{mm (Simulated)}$$

4.2. Proposed Antenna Fabrication and Measurements

The UWB with a quad-band notched antenna were fabricated and its performance tested. Figures 15(a) and (b) depict top and bottom views of the antenna layout printed on Rogers RO4003C (3.55) with volume $50 \times 40 \times 1.524\,\text{mm}^3$. Figures 16(a) and (b) depict the VNA and anechoic chamber setup for VSWR and radiation patterns measurements. Figure 11 illustrates both simulated and measured VSWR results for a UWB antenna and a quad band notched UWB antenna features. The measured and simulated peak gains are shown in Figure 13. The measured and simulated co- and cross-polarizations of proposed antenna at non-notched frequency bands are shown in Figure 14. It shows that proposed antenna has good radiation performance in out of rejection bands. The proposed antenna achieves excellent performance of simulation and measurement. Certain deviations from the measurements and simulations are caused by errors in the manufacture, feeding, and experimental operations.

(a)   (b)

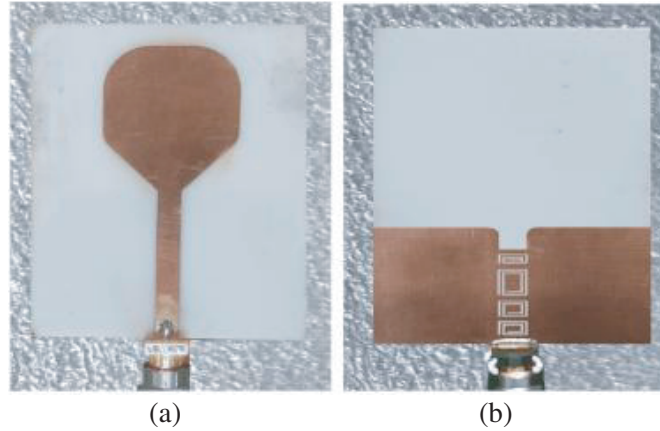**Figure 15.** fabricated layout of proposed antenna. (a) Top view. (b) Bottom view.

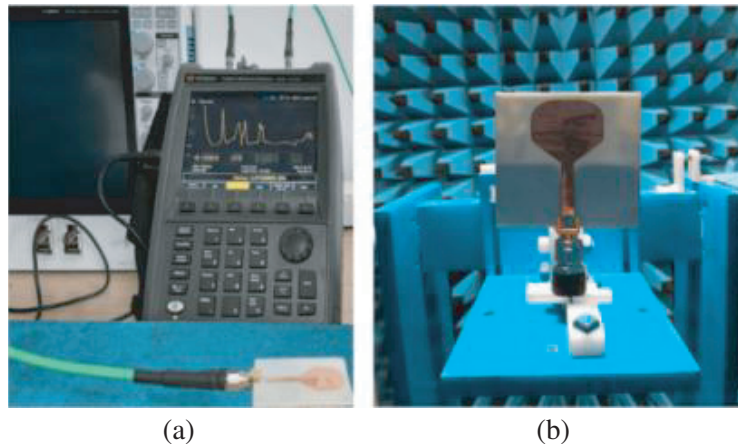(a)   (b)

Figure 16. Proposed antenna measurement hardware set-up. (a) VNA set-up. (b) Anechoic chamber.

Table 2. Previous antennas are compared to the proposed antenna.

Ref.	Notch Frequency Band/bands (GHz)	Methodology	No. of Notch bands	Size (mm³)	(Material)
1	3.5, 5.25, 5.80, 7.5	L-shape slot, complimentary split ring resonator, C-shape slots	4	$30 * 60 * 0.8$	FR4 (ER = 4.4)
3	3.6, 5.5, 7.6	electromagnetic band gap (EBG), split-ring resonators (SRRs)	3	$20 * 26 * 1.52$	Taconic, TLY-5A (ER = 2.17)
5	3.3–3.8-5.15–5.85-7.9–8.4	rectangular split-ring resonators, elliptic single complementary split-ring resonators	3	$38 * 35 * 1.6$	FR4 (ER = 4.4)
12	3.5, 5.2, 5.8	Asymmetric T-shaped open-ended stubs and J-shaped open-ended stubs	3	$25 * 30 * 1.57$	Rogers 5880 (ER = 2.2)
13	3.4, 5.6, 9	elliptical split ring resonator (ESRR), rectangular split ring resonators	3	$57 * 34 * 1$	F4B (ER = 2.65)
14	3.5, 5.5, 7.5	By two L-shaped stubs and complementary split ring resonator slot	3	$12 * 15*$	FR4 (ER = 4.4)
15	3.29–4.83, 5.15–6.84, 7.94–8.49	Meander Slot	3	$40 * 38 * 1.6$	FR4 (ER = 4.4)
This work	3.4, 5.05, 5.74, and 7.54	Spiral lossy resonator (SLR) slots are loaded into the UWB ground structure to achieve quad-band notch characteristics	4	$50 * 40 * 1.52$	Rogers RO4003C (ER = 3.55)

4.3. Proposed Antenna Mathematical Modeling and Analysis

As depicted in Figure 17, the equivalent circuit is modelled using RLC parameters, and it is then simulated and optimized using CST circuit simulation. According to the VSWR plot in Figure 18, it demonstrates an approximately good relationship between 3D and circuit models.
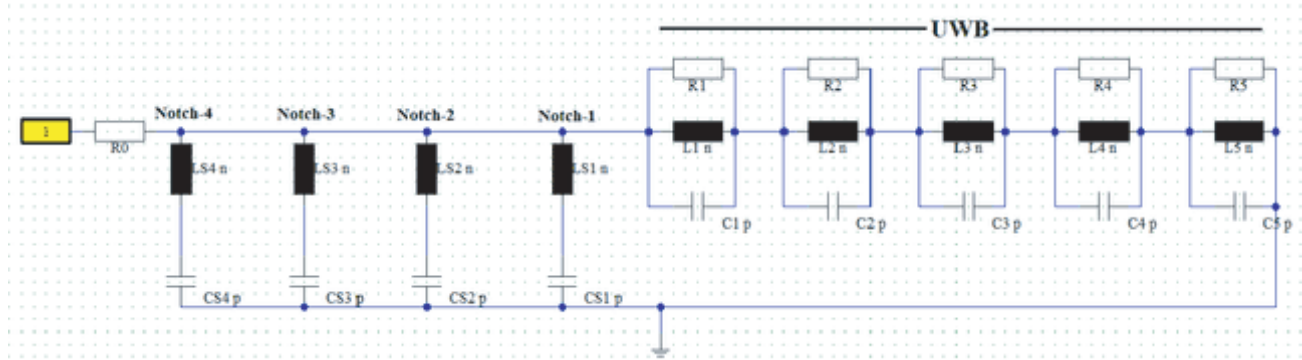

Figure 17. Illustrates the circuit simulation of proposed notch antenna.

4.3.1. Optimizes Lump Elements Parameters

$C1 = 12.977$, $C2 = 12.66$, $C3 = 10.68$, $C4 = 50$, $C5 = 48.442$, $CS1 = 2.79$, $CS2 = 1.16$, $CS3 = 1.82$, $CS4 = 0.07$, $L1 = 11$, $L2 = 11$, $L3 = 23.06$, $L4 = 46.76$, $L5 = 46.92$, $LS1 = 1$, $LS2 = 1.21$, $LS3 = 0.54$, $LS4 = 9$, $R_O = 50$, $R1 = 100$, $R2 = 196.43$, $R3 = 100$, $R4 = 99.54$, $R5 = 100$.
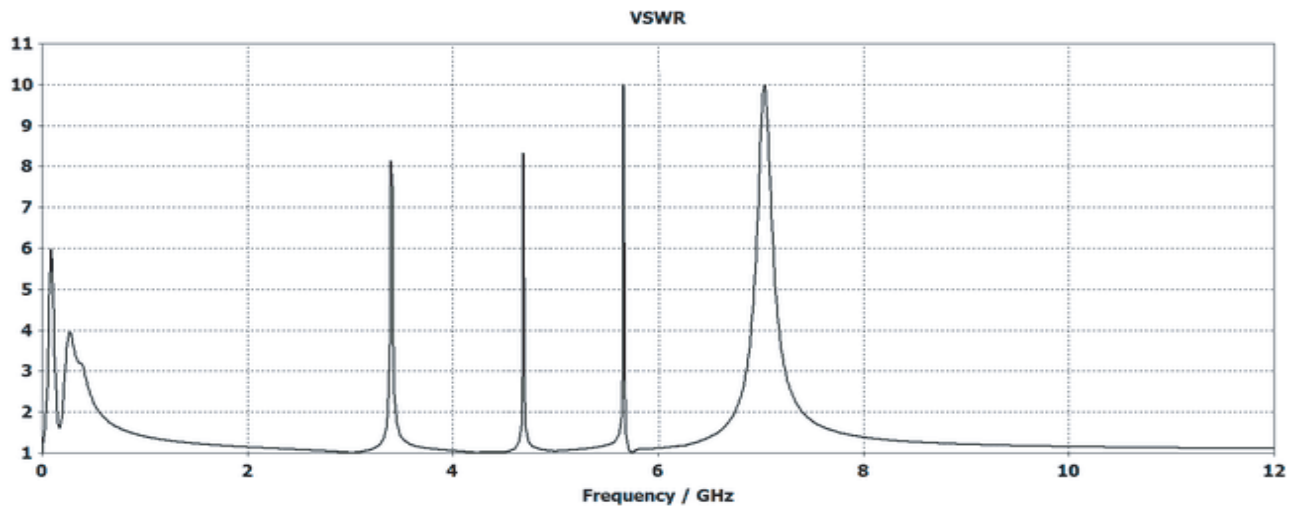

Figure 18. VSWR plot from modeling circuit of proposed antenna.

5. CONCLUSION

In this paper, a quad-band UWB notched antenna has been investigated. The quad-band notch characteristics have been achieved by loading spiral lossy resonator (SLR) slots in the bottom part of the UWB antenna. The gain, radiation efficiency at the required stopband resonance frequencies, and the current distribution of the notch characteristics antenna were utilized to demonstrate interference rejection. The proposed UWB antenna works from 2 to 12.5 GHz frequency band, except four rejected bands: WiMAX (3.24 to 3.56 GHz), L-WLAN (4.76 to 5.34 GHz), U-WLAN (5.58 to 5.91 GHz), and C-band (7.37 to 7.71 GHz). The UWB antenna with a quad-band notched could be a good fit for UWB application due to its compact dimensions, desired gain, and radiation efficiency.

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