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Design of Frequency Reconfigurable Quadruple Band Notched Ultra-Wideband Antenna

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ABSTRACT: A miniaturized ultra-wideband (UWB) antenna with quadruple reconfigurable characteristics is proposed in this paper. The first step involves the development of an elementary circular patch antenna of size $28.5 \times 28.5\,\text{mm}^2$, which is subsequently modified to demonstrate UWB properties. To incorporate quad-band notch features, the radiating surface of the patch antenna is etched with four inverted U-shaped slots. The antenna has an impedance bandwidth ranges from 3.1 GHz to 12 GHz, with four specific notches located at 3.62 GHz (3.46–3.69 GHz), 3.94 GHz (3.81 GHz–3.94 GHz), 43 GHz (4.19 GHz–4.39 GHz), and 4.84 GHz (4.61 GHz–5.05 GHz). By incorporating four PIN diodes, the antenna is capable of attaining a range of sixteen reconfigurable states across the UWB spectrum. The design of this system successfully addresses the issue of interference caused by WiMAX, satellite communication uplink C-band, Indian national satellite system, and WLAN. The prototype was constructed and evaluated, with the results from simulation and measurement correlating well.

1. INTRODUCTION

The Federal Communications Commission (FCC) has granted permission for the commercial utilization of the frequency range between 3.1 and 10.6 gigahertz (GHz) [1]. The advantages of ultra-wideband (UWB) technology, including low power consumption and high-speed communication over short distances, have generated significant attention among academics. Microstrip patch antenna is widely favored among other types of antennas because of its small size and easy fabrication procedure. The implementation of UWB systems faced a significant obstacle as a result of increasing interference caused by many narrow-band systems. UWB systems frequently experience electromagnetic interference because of the need to share the spectrum, resulting in diminished performance. A proposal has been made to incorporate a notch band feature into UWB antennas in order to address problems related to unwanted interference. Implementing a narrow band-stop filter to the antenna's output is a widely recognized method for resolving this problem. Nevertheless, this method amplifies both the intricacy and expenditure of the entire system.

Notch bands in UWB spectrum have been created using different techniques. They include introducing grooves to radiator [2–4], ground [5, 6], or feed line [7, 8]. Another way is inserting strips into a radiator [9–11]. Once these designs are produced, the notch bands become permanently set and cannot be altered. This constraint can provide difficulties in scenarios where notch bands are not needed when there is no interference from narrow-band systems. To address this issue, it is necessary to build UWB antennas that can be reconfigured dynamically and have flexible notch characteristics that can be customized according to the requirements. To enhance dynamic performance, aerial design might incorporate different types of switches, such as micro-electromechanical switches (MEMSs) [12, 13] or PIN diodes [14–20]. A triangular groove in the radiator, which has a measurement of $20 \times 20\,\text{mm}^2$, is linked to a PIN diode. This connection allows the aerial to generate a single adjustable notch specifically at the wireless local area network (WLAN) frequency. In the research conducted by [15], a PIN diode is carefully placed within a G-shaped patch to generate a single adjustable notch that encompasses both the C-band and WiMAX frequencies. The antenna has dimensions of $8 \times 27.5\,\text{mm}^2$. However, employing only one adjustable frequency band is inadequate for properly mitigating the prevalent interference within the frequency spectrum. A dual-band notched antenna with adjustable notch frequencies has been created by incorporating a PIN diode between two T-shaped strips [16]. The antenna, with dimensions of $27 \times 32\,\text{mm}^2$, is capable of reducing the strength of interfering frequencies emitted by WiMAX and WLAN. The authors in [17] have successfully built reconfigurable dual-band notch functions by employing two diodes over the substrate. These functions effectively block both WLAN and X-band signals. The dimensions of the antenna are $24 \times 32\,\text{mm}^2$. Switchable antennas with dual and triple notch features have been effectively applied in studies [18] and [19]. The study shown in [18]

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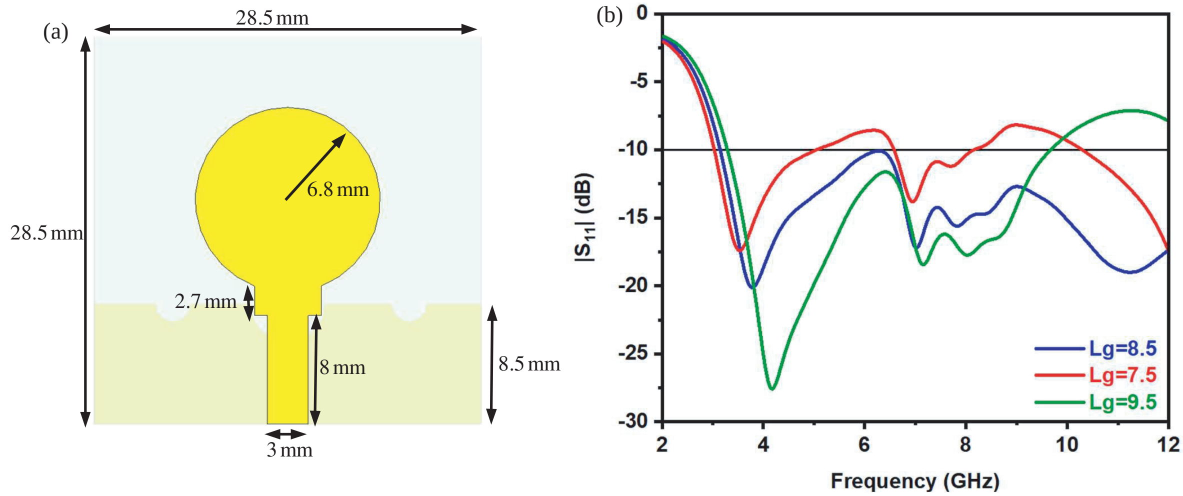

FIGURE 1. (a) Optimized UWB antenna. (b) Reflection coefficients for the suggested UWB antenna.

demonstrates the capability to manipulate notch bands for both WiMAX and WLAN by employing four diodes on strips and stubs. The dimensions of the antenna utilized in this investigation are $24 \times 32\,\text{mm}^2$. On the other hand, the research conducted in [19] accomplishes the ability to change between WiMAX and X-bands by activating a group of diodes on C-shaped slots. The dimensions of the antenna utilized in this example are $24.5 \times 20\,\text{mm}^2$. In a previous investigation, a flexible triple-notch antenna with dimensions of $20 \times 22\,\text{mm}^2$ was presented [20]. The antenna has the ability to switch among WiMAX, Wireless LAN, and X-band frequencies simply altering the design of the radiator. The antenna possesses an electrically adjustable band-notch capability, functioning in frequencies of 2.37, 3.03, and 4.18 GHz [21]. This design combines a circular patch antenna with a defected ground structure (DGS), as well as a pair of L-slot structures and slits. This configuration enables the antenna to produce dual-band notch signals at both the C-band and WLAN frequencies [22]. Paper [23] presents a new type of antenna that operates in two modes and has a small frequency range. This antenna design combines Koch fractal geometry with circular complementary split-ring resonators (CSRRs). The antenna is constructed utilizing a unique fractal curve derived from the Koch curve. The architecture incorporates two optimized circular CSRRs in order to attain dual-band characteristics. The antenna functions in dual resonance mode at frequencies of 5.1 GHz (WLAN) and 9.6 GHz (X-band), while in single-mode operation it resonates at 8 GHz (X-band). Ref. [24] presents a new compact UWB antenna based on coplanar waveguide (CPW) technology, which has the ability to alter its notch characteristics electrically. This antenna is specifically engineered for seamless integration into cognitive radio systems. The device incorporates a rectangular microstrip radiator on its lower surface to generate a specific frequency notch. This is achieved by utilizing varactors, which enable the needed tunability and downsizing. The antenna is a UWB band-notch design that is fed using CPW and enables continual adjustment of its rejection band for WiMAX. Additionally, it maintains a fixed rejection band for WLAN. This information is referenced in [25]. The authors in [26] present a concise and flexible design that incorporates configurable bandstop/bandpass capabilities using S-shaped split-ring resonators (S-SRRs). The study in [27, 28] investigates the potential for reconfigurability among WLAN and tri-bands, specifically Bluetooth, WiMAX, and higher WLAN. In addition, [29] describes a UWB antenna with reconfigurable band-notched capabilities that can transition among four different operational states. In [30, 31], various band notched reconfigurable UWB antennas are proposed.

The literature survey reveals a lack of research on reconfigurable quad-band notch functions. The current body of research solely concentrates on switchable UWB antennas including triple notches. This study introduces a compact and adaptable UWB antenna with four frequency bands that have been suppressed. The radiator incorporates a flexible design with four U-shaped slots, each of which is regulated by a PIN diode. The notch bands for WiMAX, satellite downlink C-band (for INSAT), and WLAN can be activated or deleted separately. This design allows the aerial to function in different modes, such as single, dual, triple, and quadruple band notch states, depending on the interference situations. The construction consists of a circular patch with dimensions of $28.5 \times 28.5 \times 1.6\,\text{mm}^3$, which is created on a substrate made of FR-4. The subsequent sections provide an elaborate account of the design requirements for the prototype antenna. In order to showcase the system's efficiency, a range of factors, such as S_{11}, radiation characteristics, and gain characteristics, are both simulated and tested.

2. UWB ANTENNA DESIGN METHODOLOGY

This section provides a comprehensive description of the geometric configuration and design methodology employed for the antenna under consideration. The UWB aerial is a conventional monopole antenna, whose dimensions are determined using calculations based on the transmission line model. Figure 1(a) depicts a circular radiator that has been lithographed on an FR-4

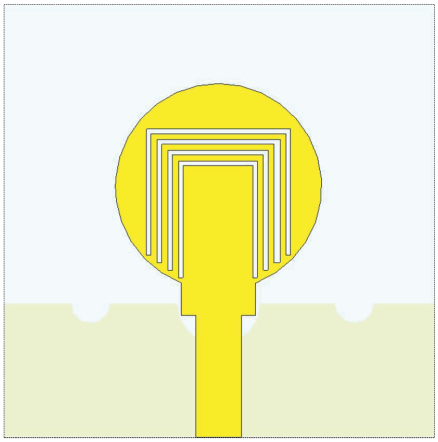

FIGURE 2. Optimized quad band notched UWB antenna.

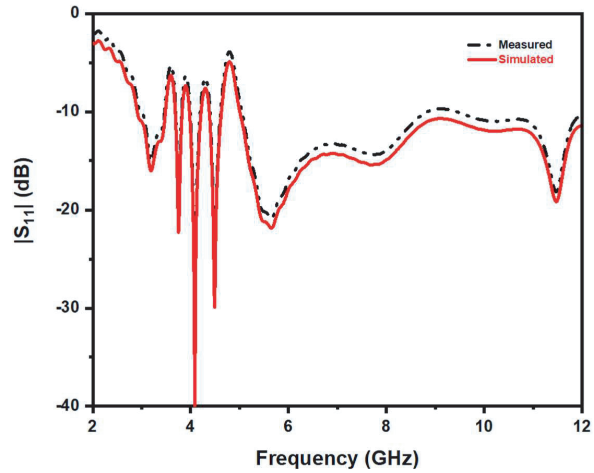

FIGURE 3. S_{11} variation with frequency.

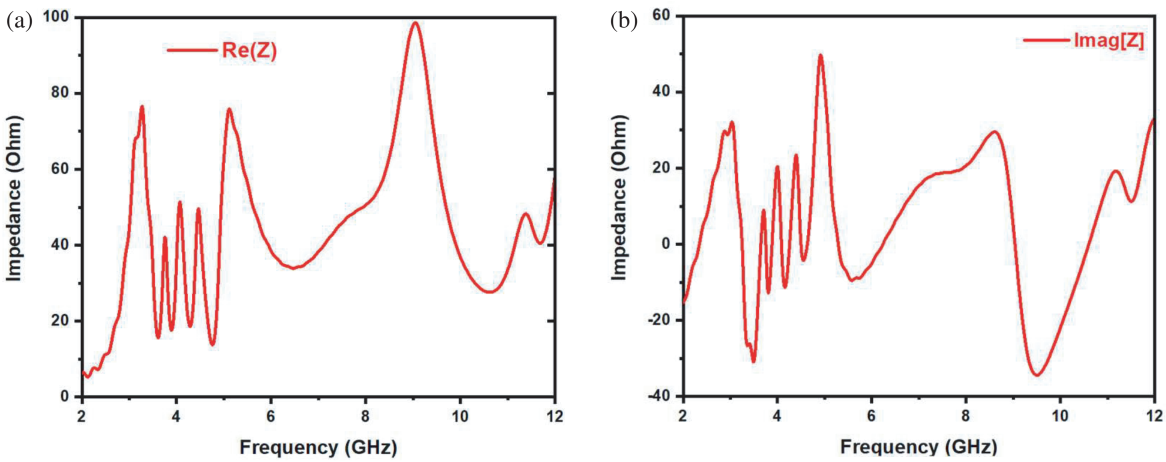

FIGURE 4. Impedance curves of the proposed UWB Antenna. (a) Real impedance. (b) Imaginary impedance.

substrate. The radiator dimensions are $28.5 \times 28.5 \times 1.6\,\text{mm}^3$. Nevertheless, the antenna's operational bandwidth fails to meet UWB standards. In order to increase the frequency range that can be used, the size of the ground plane is modified to 8.5 mm. This allows for operation in frequency band: 3.1 GHz to 12 GHz as illustrated in Figure 1(b). To establish the best possible impedance matching between the patch and the feeder, a groove with dimensions of $2 \times 3\,\text{mm}^2$ is introduced on the ground surface of the monopole. The antenna under consideration is thereafter subjected to simulation and optimization using CST MW Studio 2018.

To avoid narrow band interference, the patch antenna element was etched with four U-shaped slots (Figure 2). The optimal dimensions are: $L1 = 25.5\,\text{mm}$, $L2 = 24.3\,\text{mm}$, $L3 = 22.4\,\text{mm}$, $L4 = 20.6\,\text{mm}$.

These slots create notches at 3.62 GHz (3.46–3.69 GHz), 3.94 GHz (3.81 GHz–3.98 GHz), 4.33 GHz (4.19 GHz–4.39 GHz), and 4.84 GHz (4.61 GHz–5.05 GHz), effectively mitigating intrusion from WiMAX, C-band, Indian National Satellite System, and Wireless LAN, respectively.

Figure 3 depicts the frequency dependent return loss curve for the aforementioned band eliminated aerial.

It is evident that the aerial exhibits an operative bandwidth spanning from 3.1 GHz to 12 GHz, accompanied by quadruple notches within the UWB spectrum. The values of geometrical parameters are obtained using the equations presented below [30]

$$f_n^i = \frac{C_0}{2L_{\text{slot}}^i\sqrt{\varepsilon_{\text{eff}}}} \tag{1}$$

$$L_{\text{slot}}^i = 2Li + Wi \tag{2}$$

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2} \tag{3}$$

3. EQUIVALENT CIRCUIT ANALYSIS

In this section, we will further examine the band-rejection characteristics of the suggested UWB antenna by using an RLC equivalent circuit.

The initial concept of the equivalent circuit model is founded upon the impedance characteristics of the UWB notch band antenna as depicted in Figure 4. The antenna exhibits specific impedance values at the central notch frequencies (3.62 GHz, 3.94 GHz, 4.33 GHz, and 4.84 GHz). The resistive component of the impedance is close to 50 Ω, while the reactive component varies from negative to positive. This allows us to represent the resonance modes of the notches (slot-1, slot-2, slot-3, and slot-4) using series RLC circuits. The RLC equivalent circuit is depicted in Figure 5.

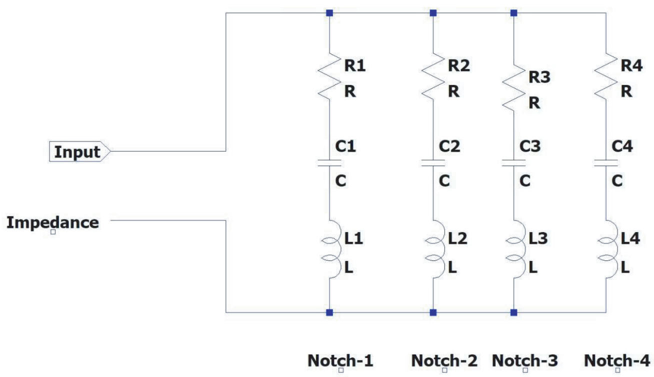

FIGURE 5. Equivalent RLC circuit.

To achieve reconfigurable functionality in the constructed band notched UWB aerial, four PIN diodes are employed to alter the notch frequencies across multiple operational modes. PIN diodes (SMP1345-040LF-Skyworks Solutions Make) are specifically chosen for switching the proposed antenna. According to the data sheet, in the active state PIN diode is substituted with series arrangement of an inductance (0.45 nH) and resistance (4 Ω). Likewise, in the inactive mode, PIN diode is substituted with an inductor (0.45 nH) in series with a parallel combination of resistor (10 kΩ) and capacitor (0.2 pF). The reconfigurable quad-band suppressed UWB aerial is illustrated in Figure 6. Prototype model of the suggested reconfigurable UWB aerial is depicted in Figure 7 with four PIN diodes positioned in four slots.

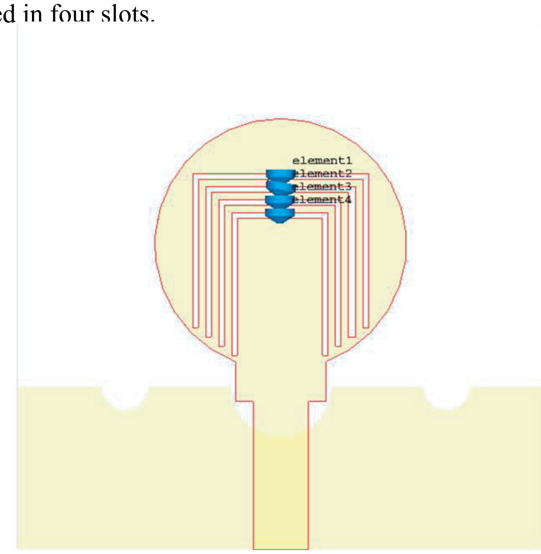

FIGURE 6. Suggested re-configurable quad band notch UWB antenna.

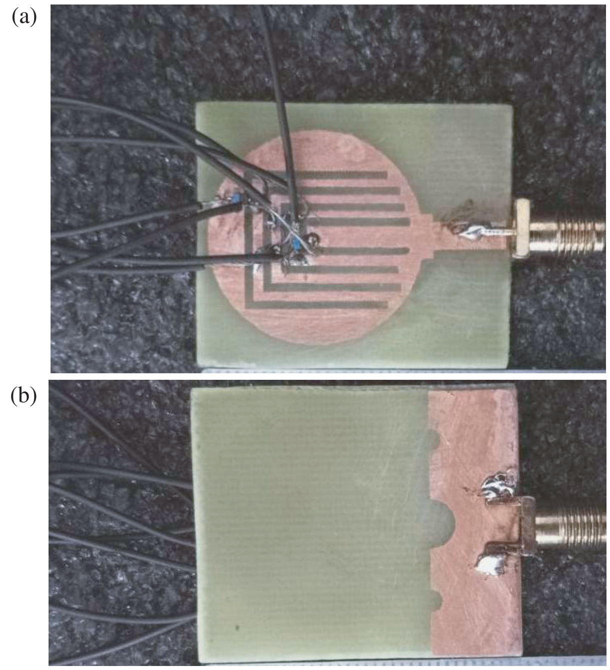

FIGURE 7. Prototype model of re-configurable quad notch band ultra wide band antenna. (a) Front view. (b) Back view.

4. PARAMETRIC ANALYSIS

To comprehend the functioning of UWB aerials equipped with quadruple notch band characteristics, we provide a comprehensive explanation of the design procedure and carry out a parametric examination. This analysis facilitates the assessment of the influence of the four U-shaped slots on the creation of the quadruple band notches. Firstly, we analyze the impact of altering the length of the outer U-shaped slot ($L1$) on the S_{11} frequency response. The introduction of slot #1 to the radiating surface results in the emergence of the first notch frequency ($fn1$). Figure 8 illustrates that by modifying the overall slot length while maintaining a constant width ($W1$) of 0.5 mm, it is possible to alter the notch frequency. Figure 8(a) demonstrates that when $L1$ increases, the notch frequency is shifted towards lower values.

By adding a second U-shaped slot (referred to as Slot #2) above the radiating surface, a second notch ($fn2$) at a frequency of 3.94 GHz is introduced. Figure 8(b) demonstrates that an increase in $L2$ results in a downward shift of the notch frequency. The third and fourth notches, appearing at frequencies of 4.33 GHz and 4.84 GHz, respectively, are created by the third U-shaped groove (Slot #3) and the innermost groove (Slot #4). The frequency dependency of the reflection coefficient for various values of $L3$ and $L4$ is illustrated in Figures 8(c) and 8(d), revealing that each U-shaped slot affects the notch frequencies.

As previously mentioned, PIN diodes are utilized to facilitate reconfigurability. The antenna may achieve sixteen separate operational modes by accurately applying bias to the PIN diodes. Tuning the first notch frequency can be achieved by adjusting diode D1 in the outside U-slot, specifically Slot #1. Diodes D2, D3, and D4 are responsible for regulating the second, third, and fourth notch frequencies. These diodes specif-

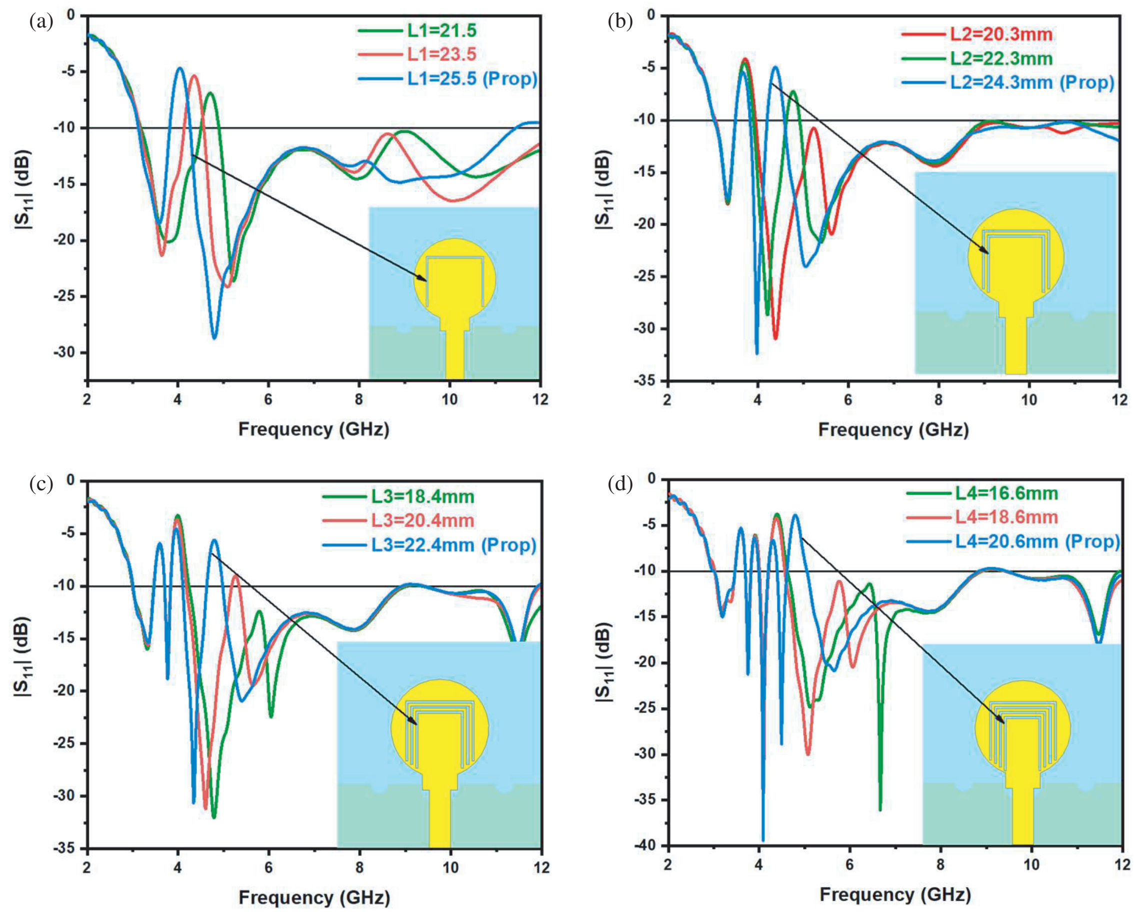

FIGURE 8. Variation in lengths of (a) slot-1, (b) slot-2, (c) slot-3, (d) slot-4.

TABLE 1. Operating states of proposed quad band notched re-configurable UWB antenna.

Mode	D1	D2	D3	D4	1st Notch	2nd Notch	3rd Notch	4th Notch
1	OFF	OFF	OFF	OFF	3.48–3.73	3.90–4.02	4.26–4.42	4.68–5.06
2	OFF	OFF	OFF	ON	3.48–3.73	3.90–4.02	4.26–4.42	-
3	OFF	OFF	ON	OFF	3.48–3.73	3.90–4.02	-	4.68–5.06
4	OFF	OFF	ON	ON	3.48–3.73	3.90–4.02	-	-
5	OFF	ON	OFF	OFF	3.48–3.73	-	4.26–4.42	4.68–5.06
6	OFF	ON	OFF	ON	3.48–3.73	-	4.26–4.42	-
7	OFF	ON	ON	OFF	3.48–3.73	-	-	4.68–5.06
8	OFF	ON	ON	ON	3.48–3.73	-	-	-
9	ON	OFF	OFF	OFF	-	3.90–4.02	4.26–4.42	4.68–5.06
10	ON	OFF	OFF	ON	-	3.90–4.02	4.26–4.42	-
11	ON	OFF	ON	OFF	-	3.90–4.02	-	4.68–5.06
12	ON	OFF	ON	ON	-	3.90–4.02	-	-
13	ON	ON	OFF	OFF	-	-	4.26–4.42	4.68–5.06
14	ON	ON	OFF	ON	-	-	4.26–4.42	-
15	ON	ON	ON	OFF	-	-	-	4.68–5.06
16	ON	ON	ON	ON	-	-	-	-

ically govern the impact of slots #2, #3, and #4, respectively. Table 1 presents comprehensive information on different operational scenarios. When all four PIN diodes are activated, an electric current passes through them, causing the antenna to operate like a typical UWB antenna. When the PIN diodes (D1, D2, D3, and D4) are not conducting, current flow is ob-

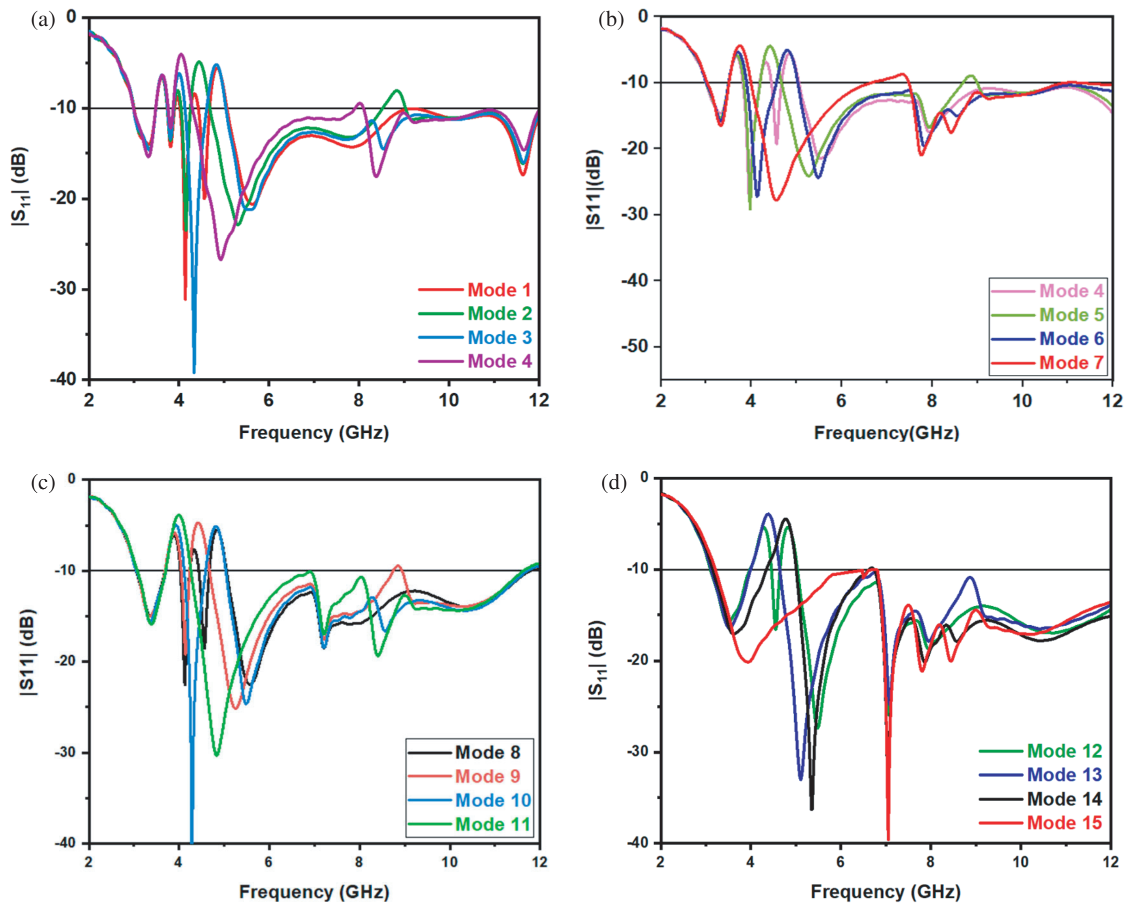

FIGURE 9. Variation of S_{11} in various modes of operation.

TABLE 2. Comparison between various Frequency Reconfigurable antennas.

Ref.	Size in mm^2	No. of notch frequencies	Notch bands (GHz)	No. of operating states	No. of Switches	Switching Diode Type	Radiation Efficiency
[21]	34.9 × 31.3	3	1.58–2.12, 2.24–2.68, 3.08–3.78	8	3	Varactor diode	85%
[23]	40 × 40	1	4.77–6.21	4	2	PIN diode	
[24]	49.4 × 35	1	3.1–5.6	2	1	Varactor diode	
[25]	50 × 50	3	GSM/LTE/ISM	8	3	Varactor diode	
[26]	45 × 40	2	3.7–4.2, 5.15–5.825	4	3	Both varactor & PIN diode	90%
[27]	20 × 20	-	-	2	3	PIN diode	70%
[28]	20 × 20	-	-	2	1	PIN diode	70%
[29]	20 × 20	2	3–4.2, 5–5.78	4	2	PIN diode	
This work	**28.5 × 28.5**	**4**	**3.46–3.69 GHz, 3.81 GHz–3.94 GHz, 4.19 GHz–4.39 GHz, (4.61 GHz–5.05 GHz.**	**16**	**4**	**PIN diode**	**82%**

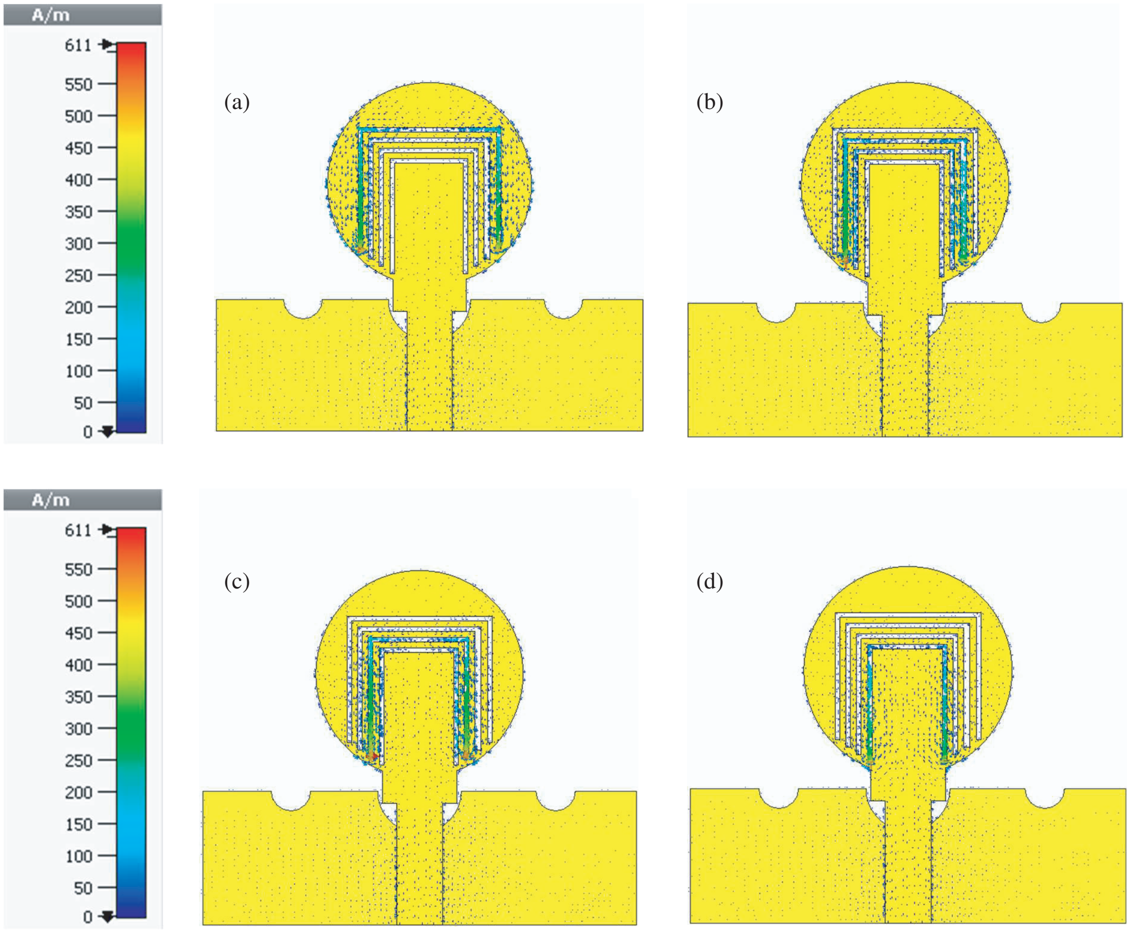

FIGURE 10. Current distribution at (a) 3.59 GHz, (b) 3.94 GHz, (c) 4.33 GHz, (d) 4.84 GHz.

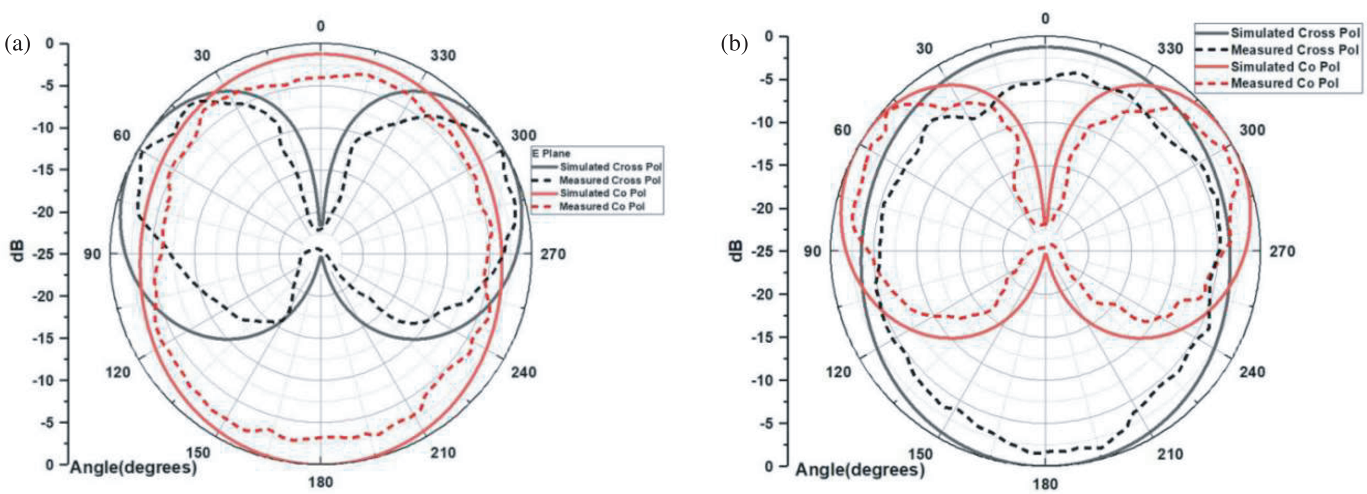

FIGURE 11. Co-pol and cross-pol radiation characteristics at 4.1 GHz. (a) E-plane. (b) H-plane.

structed, and the antenna functions as a UWB antenna with four frequency bands suppressed. Figure 9 demonstrates variation of S_{11} in various modes.

5. RESULT ANALYSIS

5.1. Surface Current density

Figure 10 illustrates the simulated fluctuation in surface current density for the reconfigurable antenna, offering valuable under-

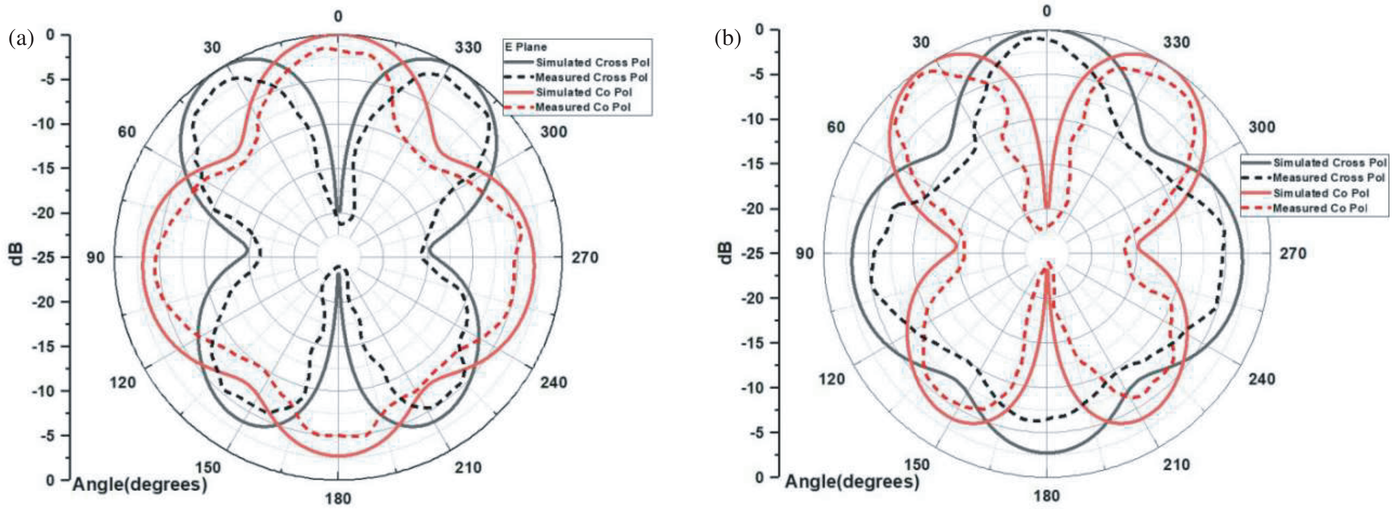

FIGURE 12. Co-pol and Cross-pol Radiation characteteristics at 6 GHz. (a) E-plane. (b) H-plane.

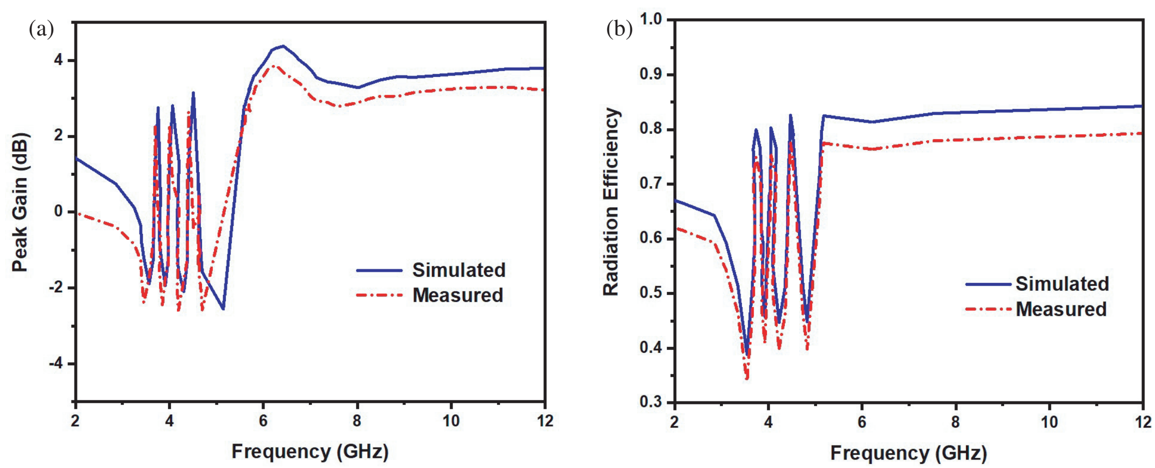

FIGURE 13. (a) Peak gain versus frequency. (b) Radiation efficiency versus frequency.

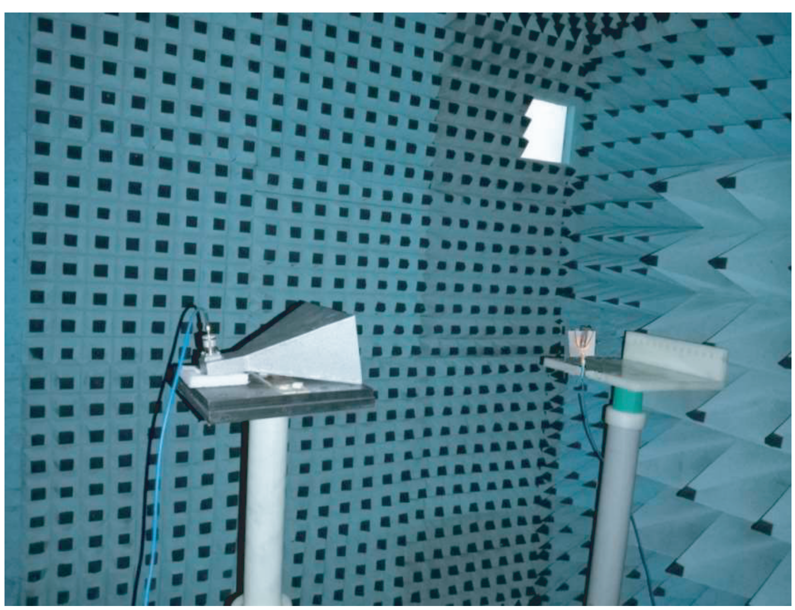

FIGURE 14. Measurement inside anechoic chamber.

standing of the generation of notch frequencies. The research reveals that the surface current is primarily concentrated around the U-shaped slots at the notch frequencies.

5.2. Radiation Patterns

Figures 11 and 12 depict the simulated and measured radiation patterns of the reconfigurable antenna for both the E-plane and H-plane. The radiation characteristics are attained for the aerial operating in the reconfigurable UWB mode (when all PIN diodes are in OFF state) and are illustrated for two resonant frequencies: 4.1 GHz and 6 GHz. The analysis of Figure 11 and Figure 12 reveals that the radiation characteristics are predominantly directed in the E-plane, while on H-plane it demonstrates omnidirectional pattern. Moreover, Figure 13 illustrates gain and radiation efficiency of the aerial. The gain plot demonstrates remarkable stability across the entire operating bandwidth of the aerial. Nonetheless, the decrease in gain is observed at the four notch frequencies, verifying the successful suppression of intrusion from WiMAX, C-band, WLAN, and Indian National Satellite System. Additionally, it is noted that the radiation efficiency remains above 82% for the whole impedance spectrum but drops to 40% at quad notches. Figure 14 depicts the photograph taken while the measurement inside an anechoic chamber. Anechoic chambers are generally of two standard shapes, i.e., rectangular and tapered ones based upon frequency of operations. The conducting walls of chamber are covered with radio frequency (RF) absorbers to obtain a reflection free environment. The reference antenna and antenna under test (AUT) are placed in the middle of the chamber in line of sight. An antenna positioner is used inside the chamber to provide three rotations (azimuth, elevation, and polarization) besides two linear motions to AUT.

Lastly, the efficacy of the proposed antenna is compared to existing literature. Table 2 provides a comprehensive comparison between the current work and existing literature.

6. CONCLUSION

A miniaturized UWB antenna with reconfigurable quadruple notch bands is investigated and presented in this paper. Four U-shaped slots are applied to realize band-notch characteristics in order to suppress unwanted frequencies at 3.62 GHz, 3.94 GHz, 4.33 GHz, and 4.84 GHz. Each notch band is independently controlled by utilizing PIN diodes to realize multimode reconfigurability. By selectively turning the PIN diode on or off, the antenna could be easily adjusted to work in distinct states. Previous literature lacks the design and development of a reconfigurable aerial with sixteen distinct cases, making this research contribution unique. The simulated and experimental results demonstrate that a UWB bandwidth covering the 3.1–12 GHz range with reconfigurable WiMAX, downlink C-band, INSAT, and WLAN rejection is obtained.

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