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Design of Ultra-Wideband Antenna with Quadruple Band Notch Reconfigurability

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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 rectangular patch antenna of size $40 \times 40\,\text{mm}^2$, 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 U-shaped slots. The antenna has an impedance bandwidth ranging from 2.2 GHz to 12 GHz, with four specific notches located at 3.3 GHz (3.1–3.5 GHz), 3.8 GHz (3.6 GHz–4 GHz), 4.6 GHz (4.5 GHz–4.7 GHz), and 5.2 GHz (5.1 GHz–5.3 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, downlink C-band, Indian national satellite system, and Wireless LAN. A prototype is fabricated and tested. The simulated and experimental results are in good agreement.

1. INTRODUCTION

The Federal Communications Commission (FCC) has granted approval for commercial usage of 3.1–10.6 GHz band [1]. Ultra-wideband (UWB) has piqued the curiosity of researchers as a result of its many benefits, including low power consumption and high-speed communication across short distances. Due to its small size and straightforward production procedure, microstrip patch antenna is a popular choice among numerous aerials available. The implementation of UWB systems faced a significant obstacle, which was the increasing interference caused by multiple narrow band systems. Due to the need for spectrum sharing, UWB systems often experience electromagnetic interference, resulting in degraded performance. The proposal of integrating a notch band feature into UWB antennas has been offered as a solution to the problems of accidental disruptions. Adding a narrow band band-stop filter to the antenna's output is a common and tried method for dealing with this issue. However, this method raises both the complexity and price of the entire system.

Notch bands in the UWB spectrum have been attained by a number of methods, such as grooves in the radiator [2–4], ground [5, 6] or in the feed line [7, 8], and incorporating strips to radiator [9–11]. Once these blueprints are manufactured, however, the notched bands are immovable. Since the notch bands are superfluous in the absence of interference from narrow band systems, this restriction becomes troublesome in certain situations. As a workaround, dynamically reconfigurable UWB antennas with notch characteristics tailored to the needs of the system need to be developed. To enable dynamic performance, it is possible to incorporate different switches into the antenna design, such as micro-electromechanical system (MEMS) switches [12, 13] or PIN diodes [14–20]. The triangle-shape groove in the radiator is connected via a PIN diode in [14]. This allows the antenna to produce a single reconfigurable notch at wireless local area network (LAN), with measurement of $20 \times 20\,\text{mm}^2$. In the study conducted by [15], a PIN diode is strategically placed in a G-shape patch to establish a singular tunable notch that encompasses both C-band and WiMAX. The dimensions of the aerial are measured to be $8 \times 27.5\,\text{mm}^2$. Nevertheless, the utilisation of a solitary switchable notch band is inadequate for effectively mitigating the prevalent interference inside the frequency spectrum. A reconfigurable dual-band notched antenna has been designed, where the reconfigurability of the notch frequencies is achieved using a PIN diode positioned between two T-shaped strips [16], while a set of PIN diodes are mounted on an elliptical split ring resonator (SRR). The aerial has the capability to attenuate the disrupting frequencies of WiMAX and Wireless LAN, measuring $27 \times 32\,\text{mm}^2$. The authors of [17] have achieved reconfigurable dual band notch functions that effectively block both Wireless LAN and X-band signals by employing two diodes on the subs. The dimensions of the aerial are $24 \times 32\,\text{mm}^2$. Switchable aerials with dual and triple notch characteristics have been successfully implemented in both studies [18, 19]. The study conducted in [18] demonstrates the ability to control notch bands on both WiMAX and Wireless LAN using four diodes on strips and stubs. The used aerial size is $24 \times 32\,\text{mm}^2$. On the other hand, the study conducted in [19] achieves recon-

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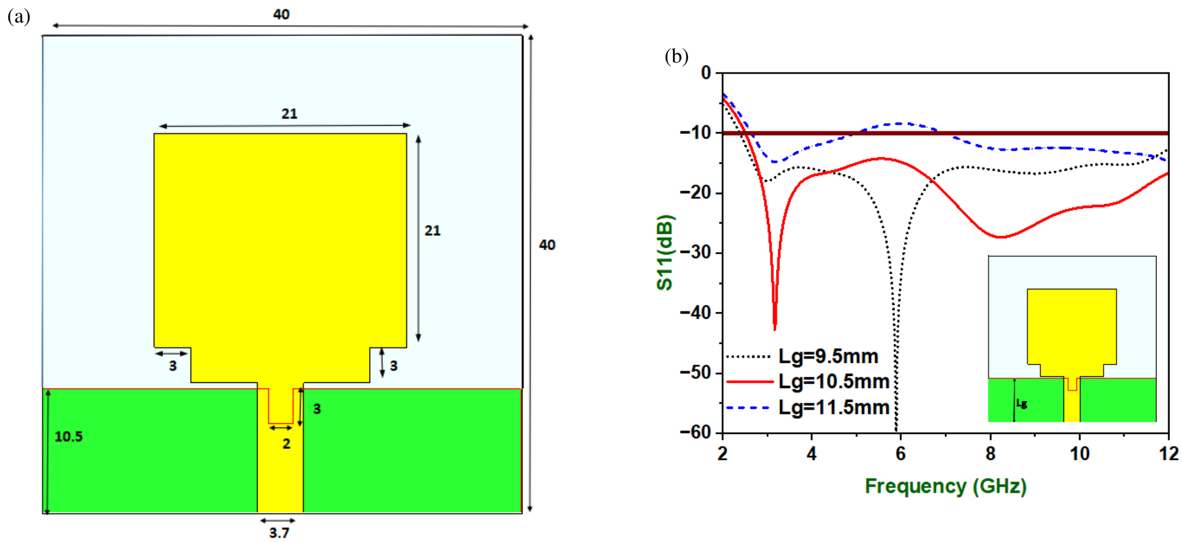

FIGURE 1. (a) Optimized UWB antenna (dimensions: mm). (b) Reflection coefficients for the suggested UWB.

figurability among WiMAX and X-bands by switching a set of diodes on C-shaped slots. The aerial size used is $24.5 \times 20\,\text{mm}^2$. In a previous study [20], a reconfigurable triple notch aerial measuring $20 \times 22\,\text{mm}^2$ was introduced. This antenna possesses the capability to toggle among WiMAX, Wireless LAN, and X-band frequencies by making adjustments to the radiator's structure. The antenna is equipped with an electronically tunable band-notched function, operating at frequencies of 2.37, 3.03, and 4.18 GHz [21]. The aforementioned design incorporates a circular patch aerial that is merged with a defected ground structure (DGS) and a pair of L-slot structures and slits. This configuration enables the antenna to create dual-band notch signals at both the C-band and Wireless LAN bands [22]. In [23], a novel dual-mode antenna with a compact frequency band is introduced, which incorporates Koch fractal geometry with circular Complementary Split-Ring Resonators (CSRRs). The aerial is designed using a unique fractal curve derived from a Koch curve. The antenna architecture incorporates two optimised circular CSRRs to attain dual band characteristics. The aerial functions in dual resonance mode, operating at both 5.1 GHz (Wireless LAN) and 9.6 GHz (X-band), and it will resonate at 8 GHz (X-band) in singular mode. The authors of [24] present a novel miniaturized coplanar waveguide (CPW) based UWB aerial that has an electrically adjustable notch behavior. This antenna is designed to be integrated onto cognitive radio systems. The aerial under consideration employed a rectangular microstrip radiator in its lower surface to establish a singular notch frequency and achieve the desired characteristics of tunability and miniaturisation through the utilisation of varactors. The antenna is a CPW-fed UWB band-notch aerial that can continually adjust its rejection band for WiMAX and also has a fixed rejection band for WLAN [25]. The authors of [26] suggest a small, adaptable (bandstop/bandpass) and adjustable construction that utilises S-shaped split-ring resonators (S-SRRs). Reconfigurability among WLAN and tribands (Bluetooth, WiMAX, and upper WLAN) is investigated in [27, 28]. A reconfigurable band notched UWB antenna which varies among four operating states is designed in [29].

Based on the literature review, it has been determined that authors have not investigated the reconfigurable quad-band notch function. The current body of literature exclusively presents switchable UWB antennas with triple notches. This work introduces a miniaturized quad-band notched UWB antenna that can be reconfigured. The radiator's four U-shaped slots, regulated by four PIN diodes, make up the flexible arrangement. The notch bands at worldwide inter-operability for microwave access, downlink C-band for satellite, INSAT, and Wireless LAN can be switched on and off independently. This allows the antenna to operate in numerous modes, including single, dual, triple, and quadruple band notch states, depending on the interference scenarios. The structure under consideration comprises a rectangular patch with dimensions of $40 \times 40 \times 1.6\,\text{mm}^3$, which has been manufactured on a Rogers RTduroid 5880 substrate. The subsequent sections provide a comprehensive description of the design specifications of the prototype aerial. In order to demonstrate the efficacy of the system, many parameters such as S_{11}, radiation characteristics, and gain characteristics are simulated and tested.

2. UWB ANTENNA DESIGN METHODOLOGY

This section focuses on the geometric configuration and design approach for the reported antenna. The reference UWB aerial is a typical monopole with dimensions obtained from transmission line model calculations. Figure 1(a) depicts a rectangular radiator lithographed onto an RT duroid 5880 substrate measuring $40 \times 40 \times 1.6\,\text{mm}^3$. Nevertheless, operative bandwidth of the aforementioned aerial does not meet the requirements of the UWB. For the purpose of increasing operative bandwidth, the ground plane's length is dropped to 10.5 mm, resulting in dual-band operation spanning between 2.56 GHz to 5.52 GHz and 6.46 GHz to 9.43 GHz as portrayed in Figure 1(b). Furthermore, the radiating bandwidth is further improved by introducing square cuts at the lowest edges of the patch aerial component. These cuts increase the electrical length of the aerial, resulting in enhanced bandwidth and enhanced impedance correlation. For ideal impedance matching among patch and the feeder, a groove with dimensions of $2 \times 3\,\text{mm}^2$ is added to the ground surface of the monopole. The suggested aerial is then simulated and optimized using CST MW Studio 2018 tool.

To avoid narrow band interference, the patch antenna element was etched with four U-shaped slots (Figure 2). The aforementioned aerial optimal dimensions are acquired as: $L1 = 13\,\text{mm}$, $L2 = 12\,\text{mm}$, $L3 = 10\,\text{mm}$, $L4 = 9.7\,\text{mm}$, $W1 = 11\,\text{mm}$, $W2 = 9\,\text{mm}$, $W3 = 7\,\text{mm}$, $W4 = 5\,\text{mm}$. These slots create notches at 3.3 GHz (3.1–3.5 GHz), 3.7 GHz (3.6 GHz–4 GHz), 4.7 GHz (4.5 GHz–4.7 GHz), and 5.22 GHz (5.1 GHz–5.3 GHz), effectively mitigating intrusion from WiMAX, C-band, Indian National Satellite System, and Wireless LAN, respectively.

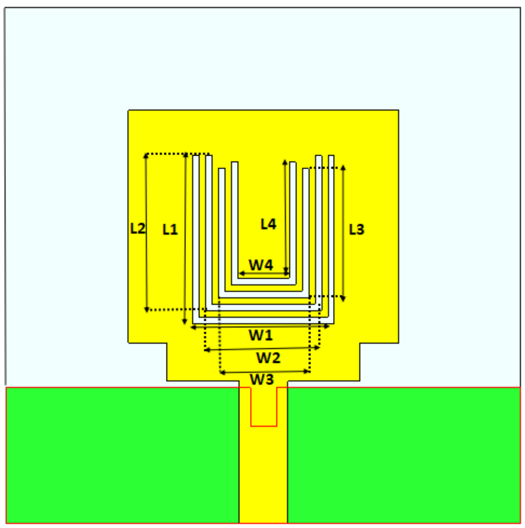

FIGURE 2. Optimized quad band notched UWB antenna.

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

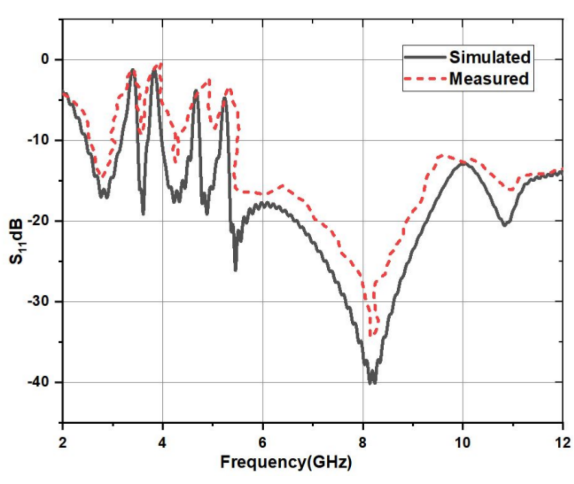

FIGURE 3. S_{11} variation with frequency.

It is evident that the aerial exhibits an operative bandwidth spanning from 2.2 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]

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

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

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

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 (3.3, 3.8, 4.6, and 5.2 GHz). The resistive component of the impedance is close to $50\,\Omega$, 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. 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 $(4\,\Omega)$. Likewise, in the inactive mode, PIN diode is substituted with an inductor (0.45 nH) in series with a parallel combination of resistor $(10\,\text{k}\Omega)$ and capacitor (0.2 pF). The reconfigurable quad-band suppressed UWB aerial is illustrated in Figure 5. Prototype model of the suggested reconfigurable UWB aerial is depicted in Figure 6. with four PIN diodes positioned in four slots.

4. PARAMETRIC ANALYSIS

In order to fully grasp how UWB antennas with quadruple notch band characteristics work, we provide the design process and parametric analysis behind their creation. To assess the significance of four U-shaped grooves in producing quadruple band notch features, parametric analysis is essential. S_{11} frequency-dependent variation is initially examined via outer U-shaped slot ($L1$) length change. Including slot #1 onto the radiating surface induces the generation of first notch frequency (f_n^1), as shown in Figure 7, and the notch frequency is tunable by amending the total slot length while the width ($W1$) is held constant at 0.5 mm. Figure 7(a) clearly demonstrates that the notch frequency moves to the left as $L1$ is increased.

The incorporation of a second U-shaped groove (slot #2) positioned above the radiating surface results in the emergence of

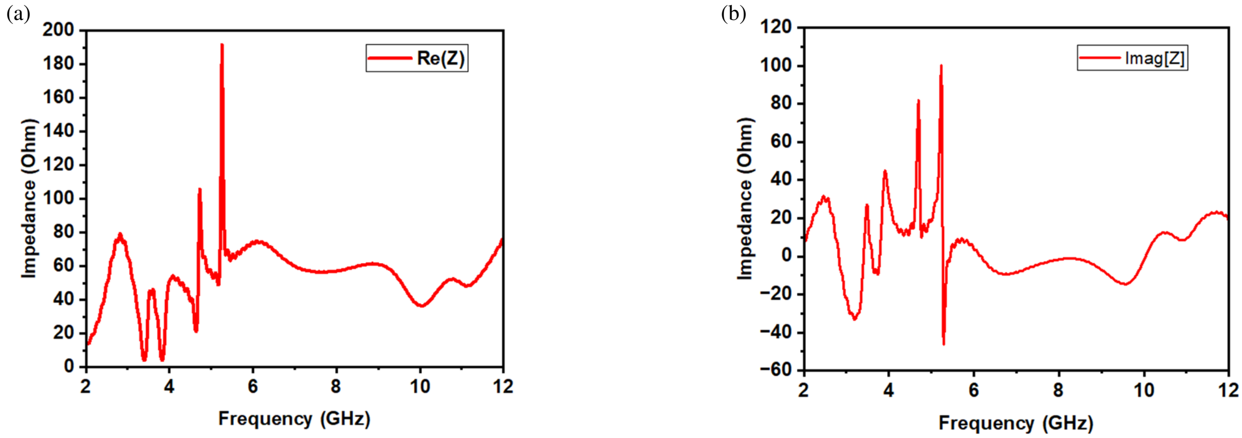

FIGURE 4. Impedance curves of the proposed UWB antenna. (a) Real impedance. (b) Imaginary impedance.

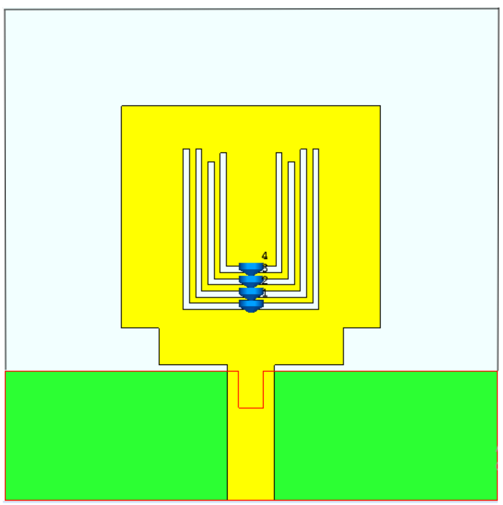

FIGURE 5. Suggested re-configurable quad band notch UWB antenna.

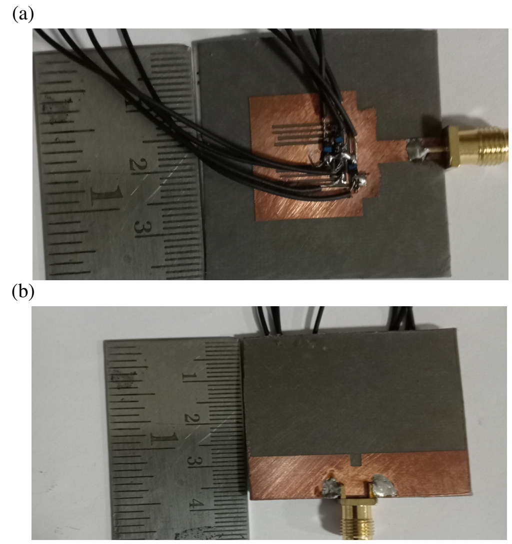

FIGURE 6. Prototype model of re-configurable quad notch band ultra wideband antenna. (a) Front view. (b) Back view.

a second notch (f_n^2) at 3.8 GHz. Figure 7(b) depicts the result of changing $L2$, indicating that a greater value of $L2$ causes the notch frequency to move to the left. Notch frequencies of 4.6 GHz and 5.2 GHz are introduced via the third U-shaped groove (slot #3) and the innermost groove (slot #4), respectively. The frequency dependence of the reflection coefficient for varying $L3$ and $L4$ is shown in Figure 7(c) and Figure 7(d). It is found that a U-shaped slot affects the notch's frequency. U-shaped slots are used as an alternative to straight slots because of the small size of the radiating patch. As indicated before, PIN diodes are typically employed to implement reconfigure characteristics. The correct application of bias across the PIN diodes has resulted in sixteen distinct working modes. By adjusting the outer U-slot (slot #1) with diode D1, the first notch frequency can be rearranged. The second, third, and fourth notch frequencies are rearranged using diodes D2, D3, and D4 to manage the impacts of slots #2, #3, and #4, respectively. Table 1 details a number of transitional scenarios. When four PIN diodes are in ON state, the current passes through them, and proposed antenna just works like a UWB antenna. When four PIN diodes (D1, D2, D3, and D4) are in OFF state, current does not pass through them, and proposed antenna works like a quadruple band notched UWB antenna.

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.

5. RESULT ANALYSIS

5.1. Surface Current Density

Figure 8 presents a simulated current variation of the reconfigurable aerial, providing valuable insights about the underlying operational principle responsible for the creation of notch frequencies. The analysis reveals that at the frequencies corresponding to the notches, the surface current concentrates primarily around the U-shaped slots. Subsequently, Figures 9 and 10 present the simulated and measured radiation patterns of the re-configurable aerial in terms of both E-plane and H-plane.

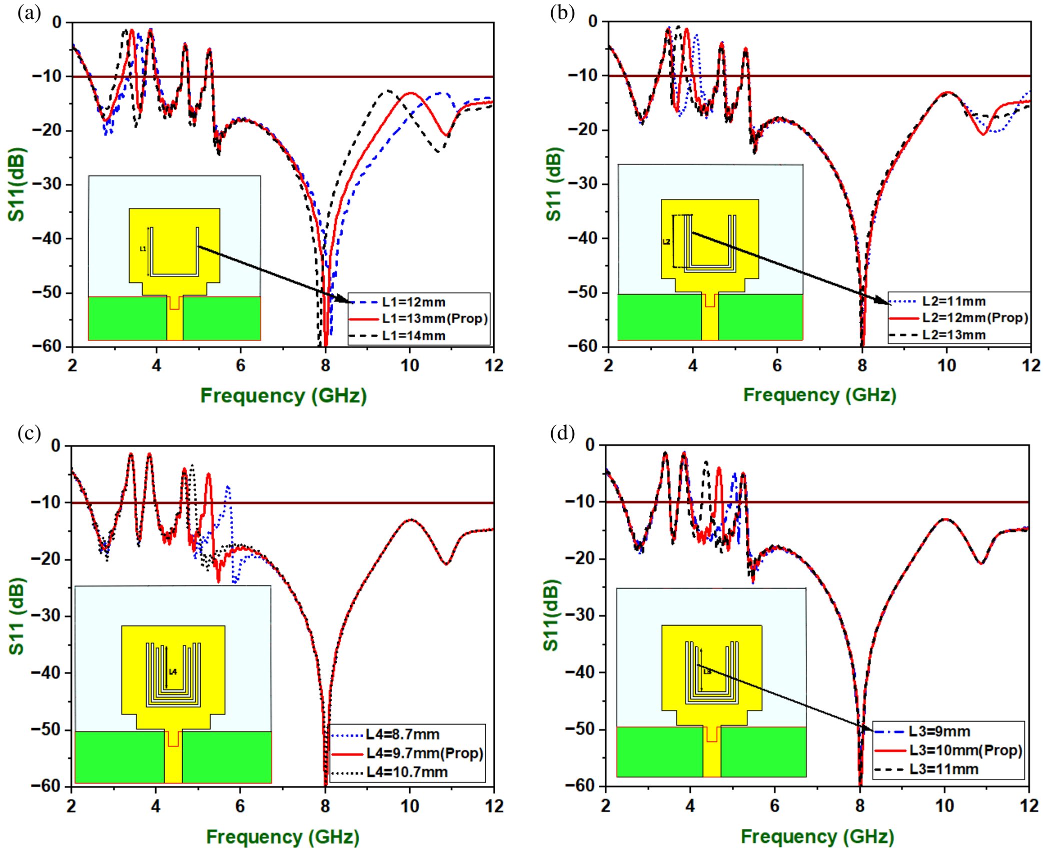

FIGURE 7. Variation in lengths of (a) slot #1, (b) slot #2, (c) slot #3, (d) slot #4.

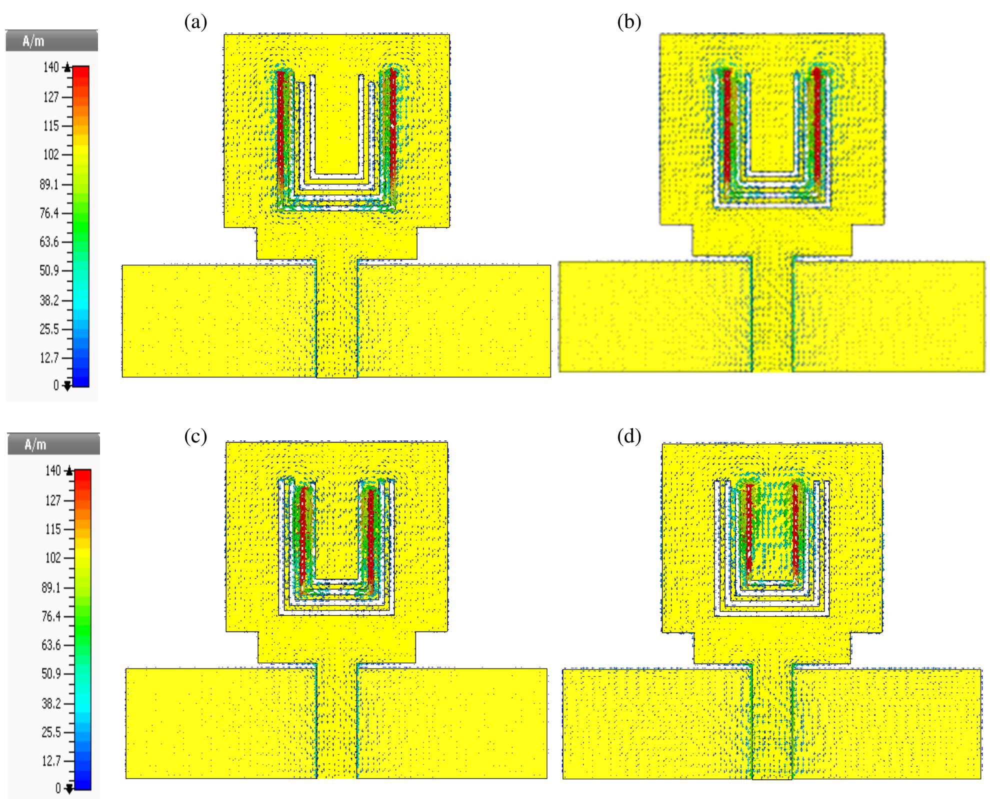

FIGURE 8. Current distribution at (a) 3.3 GHz, (b) 3.8 GHz, (c) 4.6 GHz, (d) 5.2 GHz.

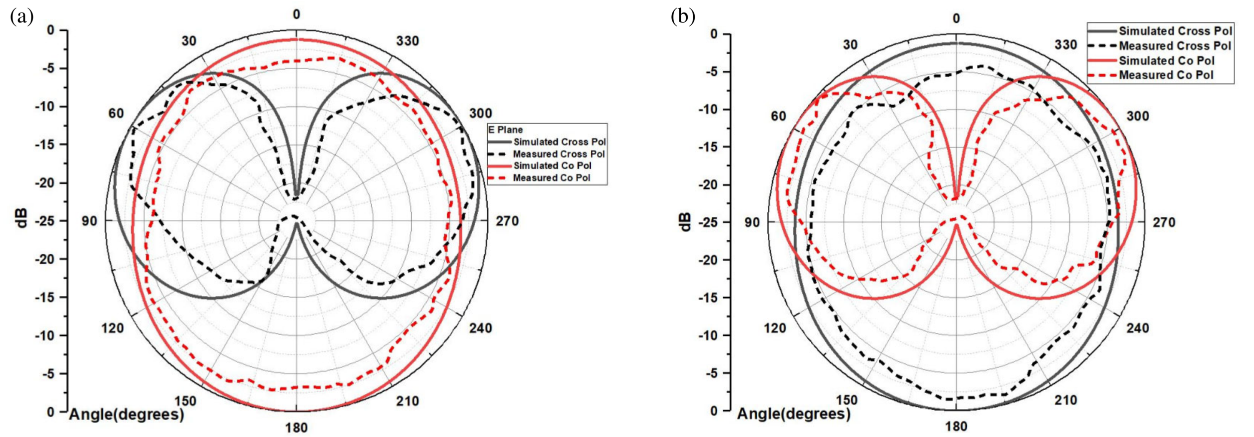

FIGURE 9. Co-pol and cross-pol radiation characeteristics at 3.6 GHz, (a) E-plane, (b) H-plane.

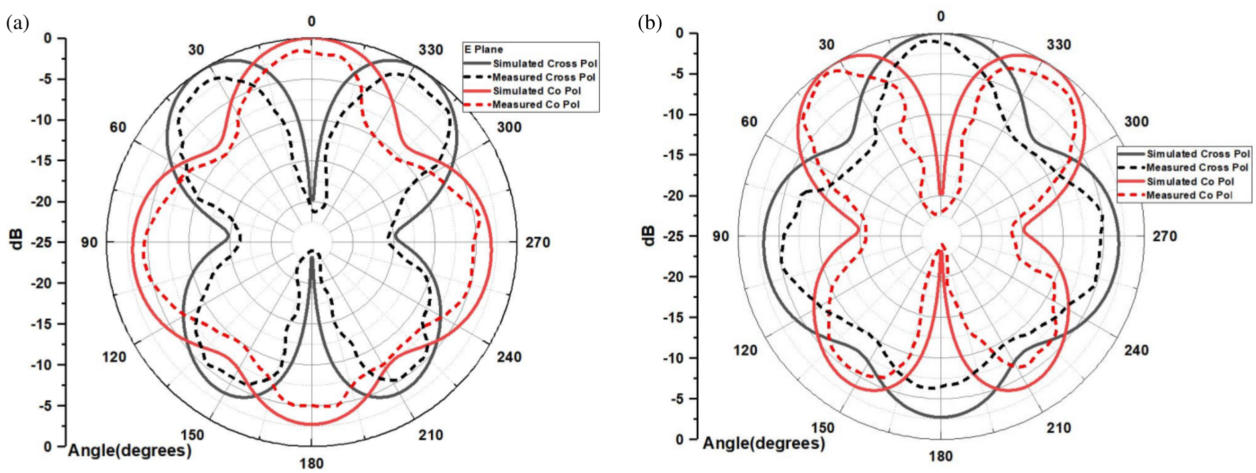

FIGURE 10. Co-pol and cross-pol radiation characeteristics at 8 GHz, (a) E-plane, (b) H-plane.

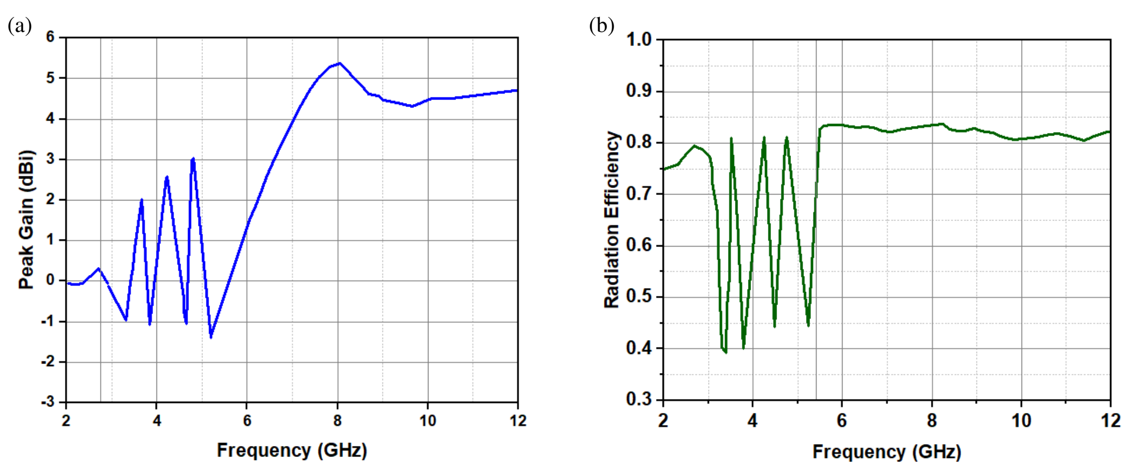

FIGURE 11. (a) Peak gain versus frequency. (b) Radiation efficiency versus frequency.

5.2. Radiation Patterns

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: 3.6 GHz and 8 GHz. The analysis of Figure 9 and Figure 10 reveals that the radiation characteristic is predominantly directed in the E-plane, while on H-plane it demonstrates omnidirectional pattern. Moreover, Figure 11 illustrates gain and radia-

TABLE 1. Operating states of proposed quad band notched reconfigurable UWB antenna.

Mode	D1	D2	D3	D4	1st Notch	2nd Notch	3rd Notch	4th Notch
1	ON	ON	ON	ON	-	-	-	-
2	OFF	ON	ON	ON	3.21–3.76	-	-	-
3	ON	OFF	ON	ON	-	3.66–4.11	-	-
4	ON	ON	OFF	ON	-	-	4.45–4.81	-
5	ON	ON	ON	OFF	-	-	-	4.98–5.25
6	OFF	OFF	ON	ON	3.16–3.54	3.7–4.15	-	-
7	ON	OFF	OFF	ON	-	3.63–3.97	4.54–4.81	-
8	ON	ON	OFF	OFF	-	-	4.38–4.73	5.08–5.29
9	OFF	ON	OFF	ON	3.18–3.69	-	4.51–4.83	-
10	OFF	ON	ON	OFF	3.16–3.77	-	-	5.08–5.28
11	OFF	OFF	ON	ON	3.16–3.55	3.68–4.14	-	-
12	OFF	OFF	OFF	ON	3.22–3.51	3.67–3.98	4.55–4.85	
13	OFF	OFF	ON	OFF	3.16–3.51	3.7–4.07	-	5.08–5.28
14	OFF	ON	OFF	OFF	3.16–3.69	-	4.57–4.76	5.14–5.33
15	ON	OFF	OFF	OFF	-	3.61–3.96	4.59–4.76	5.16–5.3
16	OFF	OFF	OFF	OFF	3.15–3.53	3.67–3.98	4.56–4.73	5.12–5.29

TABLE 2. Coparimson between various frequency reconfigurable antennas.

Ref.	Size in mm	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	$\mathbf{40 \times 40}$	**4**	**3.1–3.5, 3.6–4, 4.58–4.74, 5.14–5.3**	**16**	**4**	**PIN diode**	**80%**

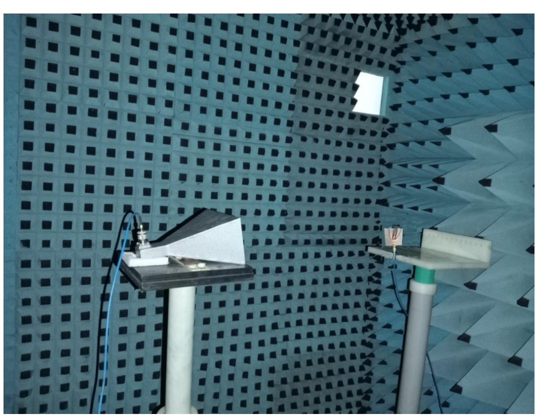

FIGURE 12. Measurement inside anechoic chamber.

tion efficiency of the aerial. The gain plot demonstrates remarkable stability across the entire operating bandwidth of the aerial. Nonetheless, decrease in gain is observed at the four notch frequencies, verifying the successful suppression of intrusion from WiMAX, C-band, Wireless LAN, and Indian National Satellite System. Additionally, it is noted that the radiation efficiency remains above 80% for the whole impedance spectrum but drops to 50% at quad notches. Figure 12 depicts a 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 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. Antenna positioner is used inside the chamber to provide three rotations (azimuth, elevation, and polarization) besides two linear motions to AUT.

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 3.3, 3.8, 4.6, and 5.2 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 2.2–12 GHz range with reconfigurable WiMAX, downlink C-band, INSAT, and WLAN rejection is obtained.

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