Titre: Title:	Frequency-Agile WLAN Notch UWB Antenna for URLLC Applications
Auteurs: Authors:	Amir Haider, MuhibUr Rahman, Hamza Ahmad, Mahdi NaghshvarianJahromi, Muhammad Tabish Niaz, & Hyung Seok Kim
Date:	2021
Type:	Article de revue / Article
Référence: Citation:	Haider, A., Rahman, M.U., Ahmad, H., NaghshvarianJahromi, M., Tabish Niaz, M., & Seok Kim, H. (2021). Frequency-Agile WLAN Notch UWB Antenna for URLLC Applications. Computers, Materials & Continua, 67(2), 2243-2254. https://doi.org/10.32604/cmc.2021.015613

Computers, Materials & Continua
DOI:10.32604/cmc.2021.015613
Article

Frequency-Agile WLAN Notch UWB Antenna for URLLC Applications

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Received: 20 November 2020; Accepted: 16 December 2020

Abstract: This paper introduces a compact dual notched UWB antenna with an independently controllable WLAN notched band integrated with fixed WiMAX band-notch. The proposed antenna utilizes a slot resonator placed in the main radiator of the antenna for fixed WiMAX band notch, while an inverted L-shaped resonator in the partial ground plane for achieving frequency agility within WLAN notched band. The inverted L-shaped resonator is also loaded with fixed and variable capacitors to control and adjust the WLAN notch. The WLAN notched band can be controlled independently with a wide range of tunability without disturbing the WiMAX band-notch performance. Step by step design approach of the proposed antenna is discussed and the corresponding mathematical analysis of the proposed resonators are provided in both cases. Simulation of the proposed antenna is performed utilizing commercially available 3D-EM simulator, Ansoft High Frequency Structure Simulator (HFSS). The proposed antenna has high selectivity with experimental validation in terms of reflection coefficient, radiation characteristics, antenna gain, and percentage radiation efficiency. The corresponding measured frequency response of the input port corresponds quite well with the calculations and simulations in both cases. The proposed antenna is advantageous and can adjust according to the device requirements and be one of the attractive candidates for overlay cognitive radio UWB applications and URLLC service in 5G tactile internet. The proposed multi-functional antenna can also be used for wireless vital signs monitoring, sensing applications, and microwave imaging techniques.

Keywords: WiMAX; UWB; lower and upper WLAN; single/dual notch behavior; independent controlling notched behavior; tunable band-notch behavior; overlay cognitive radio applications; frequency-agile WLAN notched antennas; 5G; URLLC; tactile internet

1 Introduction

The lack of existing spectrum for adjusting additional services and existing services under current use has fueled recent research based on different communications ideas since last year. Therefore, it is suggested that the unlicensed secondary users can utilize the portion of the allocated spectrum under the condition that the main licensed primary user is not affected as long. Cognitive radio (CR) was suggested and developed to enhance the overcrowded radio-frequency spectrum's supervision and deployment. It possesses wireless sensing, adapting, and using a tentatively idle spectrum, termed a spectrum hole. Interweave, overlay, and underlay are three main cognitive radio network paradigms that utilize different interaction techniques between secondary and primary users [1].

In the interweave method, the corresponding secondary users identify the non-existence signals of the primary user in corresponding time, space, or frequency and resourcefully communicate for the period of these absences [2,3]. The corresponding secondary users need to manage the corresponding primary users below the dedicated noise floor in the underlay methodology. Thus, stringent restrictions are enforced on their transmission power. One possible technique to accomplish such a task is to spread the corresponding transmitted signals of secondary users over the UWB spectrum, leading to a high data rate with low power communication. In this regard, to underlay UWB cognitive radio communication, we need a wideband antenna without band rejection capabilities. However, for overlay UWB methodology, the corresponding UWB antenna placed at the front end of the cognitive radio apparatus need to be functioning at the whole UWB spectrum, for the corresponding sensing and locating active bands of the primary users with corresponding notch band functionality with some narrowband to prevent the interference to the main primary users [4]. In some cases, such as WLAN, where we have lower WLAN (5.15–5.35 GHz; and upper WLAN (5.725–5.825 GHz), this needs to be tunable as well.

In 2002, the Federal Communication Commission (FCC) had officially allowed the communication between UWB appliances to be performed in the frequency range of 3.1 GHz to 10.6 GHz with corresponding regulator aspects including power spectral density (PSD) emission restriction for UWB transmitters is −41.3 dBm/MHz [5]. Since the UWB spectrum possesses a wide range of frequencies that include other frequency bands, these bands have corresponding electromagnetic interference with UWB appliances and need to be minimized as possible. One such solution proposed in the literature is the design and advancement of band notched UWB antennas that can be placed at the transmitter and receiver side to reduce interference. A tremendous amount of research has been performed in this regard, and different UWB antennas are developed with corresponding band-notch characteristics in [6–12]. The design approach of these antennas is different and uses other techniques and geometrical configurations to filter the interfering bands. However, the overall structures' objective is the same to band-notch these narrow frequency bands from the UWB spectrum. These interfering bands include WiMAX, WLAN (upper and lower WLAN), uplink, and downlink of X-band for satellite communication [8]. Some attempts are made to notch WiMAX and WLAN bands; however, limited attention has seen towards the tunable band notch behavior that will be attractive for cognitive radio applications [9]. Some investigations are also seen on the time domain characteristics of band-notch UWB antennas, as discussed in [10]. Some attempts are also seen between switching antennas from wideband to switchable one; however, it cannot solve such an issue [11].

In [12], the authors investigated the band rejection capabilities of UWB antennas and developed a dual notched antenna employing parasitic strips. Similarly, in [13] they designed a triple band notched UWB antenna having the potential to eliminate WiMAX, lower, and upper WLAN bands from the UWB spectrum while employing independent parasitic strips. All notched bands can be controlled independently via changing antenna parameters. The authors in [14] developed a low-cost CPW antenna having the capability of frequency reconfiguration and claimed that the proposed concept could be extended filtering applications. In [15], they tried to enhance the bandwidth of the dual-band rejected UWB antenna by employing dual nested C-shaped stubs on the patch's backside for dual notch behavior and a trident feeding technique to enhance the overall from bandwidth 7.5 GHz to 21.9 GHz. A compact CPW fed antenna integrated with filtering characteristics to switch between the narrowband and wideband is proposed in [16]. In [17], they provided a quad band-notched UWB antenna based on the analysis of CSRR (complementary-split-ring-resonators) to the CSRR coupling technique and extracted the corresponding matrices. The proposed concept is extended to rectangular slot resonators in [18], where the authors have achieved a quintuple band-notched characteristic by employing the combination of RSRR (rectangular-split-ring-resonators) and RCSRR (rectangular-CSRR). Similarly, authors in [19] achieved a dual characteristic in the UWB antenna by employing the concept of elliptical resonators. The proposed concept is extended to multiple band rejections in [20] by printing MSRR (multiple-split-ring-resonators) on the interior of the internal patch of the UWB reference antenna.

In [21], the antenna's bandwidth is enhanced to wideband by integrating the UWB filter opposite to the feeding side of the frequency scanning antenna for wireless vital signs detection applications. A triple band notched UWB antenna with the smallest form factor is proposed in [22] along with bandwidth enhancement characteristics. A tunable UWB band-notched antenna is recently introduced in [23], which can operate from 1.98 to 10.54 GHz with corresponding notched bands at center frequencies of 2.30, 3.05, and 4.10 GHz, respectively. All the notched bands are electronically controlled through varactor diodes placed in the middle of the CSRR employed for band notching behavior. In [24], they provided a small UWB band-notched antenna and then integrated a corresponding Bluetooth while utilizing capacitors loaded resonators. Also, time-domain investigations of different UWB antennas with band notch performances are done in [25,26].

A band rejected reconfigurable antenna for UWB application is reported in [27] that utilizes L-shaped strips on the main radiator and corresponding L-shaped slots on the partial ground plane for band-notching behavior. Two PIN diodes are employed to reconfigure the rejection bands. A miniature reconfigurable and frequency-tunable antenna structure established on S-shaped resonators is proposed in [28]. To reconfigure the proposed structure from band-stop to band-pass, a PIN diode is utilized and can be used as a reconfiguration structure. An efficient UWB antenna with frequency band-notched and tunability attributes is suggested in [29] for cognitive radio applications. Two band notches are established at WiMAX and WLAN frequency bands, and it is controlled electronically and independently. The whole frequency-agile fractional bandwidth is almost 74.5%, which is quite promising. A tunable filtering UWB antenna is recently proposed in [30] that have the capability of operating at 3.1 to 10.6 GHz frequency range with corresponding J-shaped stubs with a combination of T-shaped asymmetric open-ended stubs for generating notching functionality in the UWB spectrum within frequency ranges of 3.5 GHz, 5.2 GHz, and 5.8 GHz for corresponding WiMAX, lower WLAN, and upper WLAN frequency bands. Then the center frequencies of these notched bands are continuously tuned by employing varactors utilized in the design.

This article presents a compact dual notched UWB antenna with an independently controllable WLAN notched band integrated with a fixed WiMAX band-notch. The proposed antenna utilizes a slot resonator placed in the main radiator of the antenna for a fixed WiMAX band notch, while an inverted L-shaped resonator integrated with capacitors for tuning and adjusting the WLAN notched band. The WLAN notched band can be controlled independently with a wide range of tunability without disturbing the WiMAX band-notch performance. The proposed antenna has high selectivity with experimental validation in terms of reflection coefficient parameter, radiation characteristics, antenna gain, and efficiency. The proposed antenna is advantageous and can adjust according to the device requirements and be one of the attractive candidates for overlay cognitive radio UWB applications as well as for URLLC service in 5G tactile internet.

The arrangement of this paper is performed in the following approach. Section 2 discusses the resonators utilized for band notching and its guidelines via a mathematical approach. This section is further divided into two. The formal one provides design guidelines for the WiMAX band notch resonator, and the latter is responsible for tunable WLAN band notch performance. Section 3 provides the detailed geometrical dimensions of the proposed tunable WLAN band notched UWB antenna. Section 4 focuses on important results with corresponding discussions regarding the reflection coefficient parameter, antenna radiation patterns, antenna gain, and percentage radiation efficiency. Finally, the proposed work is briefly summarized in the conclusion section as Section 5.

2 Design Guidelines for the Proposed Antenna

This section will provide the mathematical analysis and the design guidelines for the proposed resonators utilized for fixed and tunable band notch characteristics in reference UWB antenna.

2.1 Initial Choice of the Resonator Dimensions Utilized for WiMAX Band Notching

For the initial selection of the resonator utilized for WiMAX band notching, the overall length (L_i) of the resonator is given as an Eq. (1) with notched frequency center band as f_{notch}:

$$L_i = \frac{\lambda_g}{2} = \frac{c}{2f_{notch}\sqrt{\varepsilon_{eff}}} \tag{1}$$

where,

$$L_i = (2 \times L_5) + (2 \times W_9) + (4 \times W_{10}) \tag{2}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{w_f}\right)^{-0.5} \tag{3}$$

λ_g signifies the corresponding guided wavelength at the chosen frequency, ϵ_r and ϵ_{eff} represent the relative and effective permittivity of the utilized substrate, respectively, and W_f shows the feedline width. After initial length selection, it is further optimized using the parametric simulations and made optimum. The optimized parameter values are then mentioned in Tab. 1.

2.2 Initial Choice of the Resonator Dimensions Utilized for Tunable WLAN Band Notching

The resonator employed for tunable WLAN band notching is selected by following a sequence of the following equations from (4) to (9) [11]:

$$\Gamma = k \pm \sqrt{k^2 - 1} \tag{4}$$

$$k = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \tag{5}$$

Table 1: Dimensions (in millimeters) of the proposed tunable WLAN notched UWB antenna

Parameters	L1	W6	W7	H	T	X
Value	17.5	2.3	3.6	1.5	0.017	0.6
Parameters	L2	W1	W2	W4	W3	W5
Value	16	24	22	6.3	10.6	3.5
Parameters	L5	L4	W8	W10	G2	Y
Value	6.5	13.86	13	2.5	0.5	4.3
Parameters	L6	L7	W9	G1	W11	—
Value	5.8	0.5	9	0.25	0.5	—

$$Z_{eff} = \sqrt{\frac{\mu_{eff}}{\varepsilon_{eff}}} = \left(\frac{1+\Gamma}{1-\Gamma}\right)\frac{Z^{TL}}{Z_a^{TL}} \tag{6}$$

$$n = n' - jn'' = \sqrt{\varepsilon_{eff}\mu_{eff}} = \pm\frac{c}{j\omega l}\cosh^{-1}\left(\frac{1-S_{11}^2-S_{21}^2}{2S_{21}}\right) \tag{7}$$

$$\varepsilon_{eff} = \varepsilon'_{eff} - j\varepsilon''_{eff} = \frac{n}{Z_{eff}} \tag{8}$$

$$\mu_{eff} = \mu'_{eff} - j\mu''_{eff} = n \times Z_{eff} \tag{9}$$

where, the reflection coefficient is represented by Γ, the characteristic impedance of the corresponding transmission line in case of air-filled is signified by Z_a^{TL}, the characteristic impedance of the developed reference transmission line by Z^{TL}, with corresponding effective length (l), and refractive index (n).

The coupling coefficient is computed using the following relations:

$$n = \sqrt{\frac{Z_{(cpw)}}{Z_{os}}} \tag{10}$$

where, $Z_{(cpw)}$ signifies the co-planar waveguide characteristics impedance, and Z_{os} represents the characteristics impedance of the utilized slot line resonator. The S_{11} and S_{21} are computed by assuming the selected resonator as a matched two-port filter. If the capacitor has got lower value, it will behave as an open circuit, while increasing its value will shift the resonance frequency. Subsequently, tunable characteristics can be established using this approach.

3 Proposed Antenna Geometry

The proposed tunable WLAN notched UWB antenna is constructed employing conventional UWB geometry as a reference structure [25]. The substrate employed for this objective is Rogers RO4003 with a related thickness of almost 1.5 mm and the corresponding relative dielectric constant having 3.38 fed by a 50-ohm microstrip line. The whole antenna dimensions are $24 \times 30.5 \times 1.5$ mm^3. Other important geometrical parameters of the proposed tunable WLAN notched UWB are listed in Tab. 1. The proposed antenna comprises a slot resonator in the main radiator for a fixed WiMAX notch band, while an inverted pair of L-shaped resonators in the partial ground plane for adjusting and tuning the WLAN notched band. The overall geometrical dimensions of the proposed WLAN notched UWB antenna is shown in Fig. 1. It must be noted that in this article, we have used four capacitors, which are, according to the American Technical Ceramics (ATC) design kit as labeled as Cap1 (fixed) and Cap2 (variable). These capacitors' position is selected based on the parametric analysis of the proposed resonator discussed in detail in [26]. Commercial electromagnetic simulator Ansoft HFSS (High-Frequency-Structure-Simulator) is used for the simulation purpose which is based on the finite element method. For further validation, the proposed antenna is also simulated in a finite difference time domain algorithm based commercially available simulator CST (Computer Simulation Technology) studio suite. Good agreement has been seen between two simulators, and for convenience, we have only correlated HFSS simulations here.

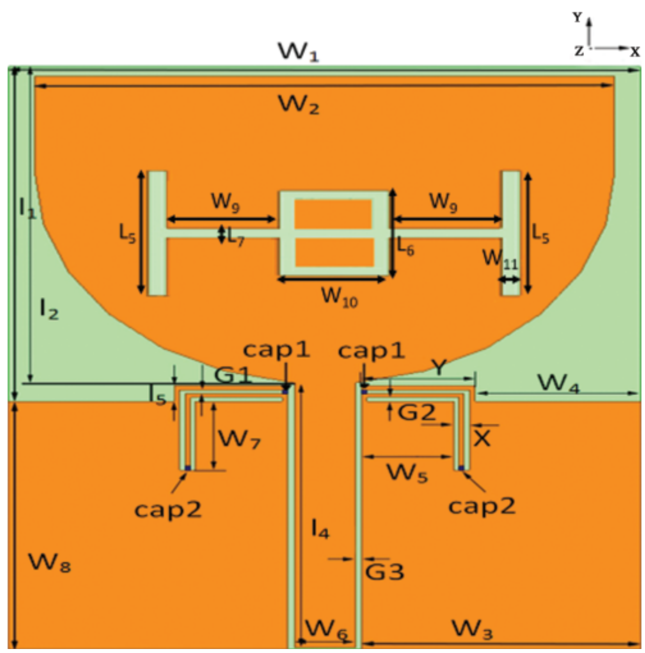

Figure 1: Dimensions of the proposed tunable WLAN notched UWB antenna

4 Results and Discussion

The proposed antenna is designed, simulated, and fabricated for validation. The antenna is designed to attain the desired UWB performance with corresponding fixed WiMAX band rejection along with tunable WLAN notching. Fig. 2 indicates the response of the proposed antenna at cap2 = 0.1 pF. It can be observed that the antenna operates in the UWB band having WiMAX notched band (3.5 GHz) and another notched band at 7.1 GHz. The second notched band can be easily made tunable to cover both upper and lower WLAN band rejection capabilities. So, by changing cap2 = 0.8 pF of the proposed antenna, the WiMAX notched band is still at 3.5 GHz (fixed) while the upper notched band is shifted from 7.1 GHz to 5.85 GHz (upper WLAN) as shown in Fig. 3. Further, increasing cap2 from 0.8 pF to 1.3 pF, the upper band is independently shifting from 5.9 GHz to 5.45 GHz (lower WLAN) with fixed WiMAX band notch as demonstrated in Fig. 4. In all three cases, the antenna is simulated, and the corresponding measured results taken from the HP-8720 vector network analyzer (VNA) are correlated with Ansoft HFSS simulations. It is seen that at cap2 = 1.3 pF, the measured results are still in a valid range to the simulated ones. This behavior can be well understood from Fig. 2 to Fig. 3 in a sequence.

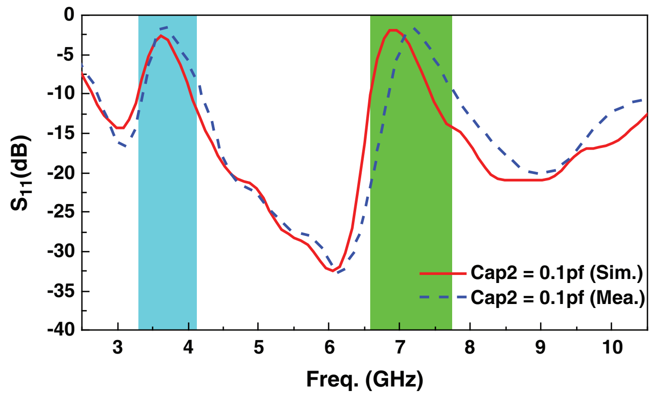

Figure 2: S11 response of the tunable WLAN notched UWB antenna having cap2 = 0.1 pF

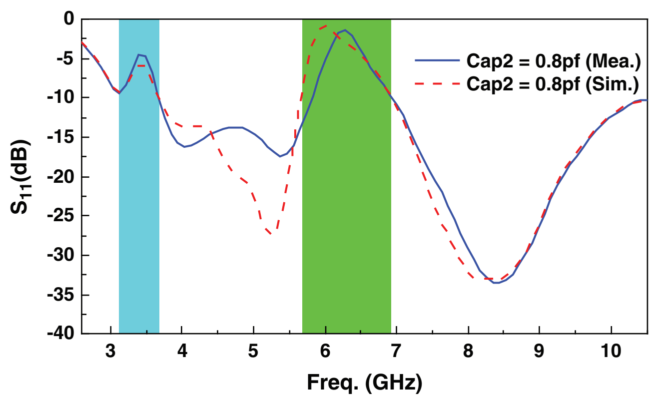

Figure 3: S11 response of the tunable WLAN notched UWB antenna having cap2 = 0.8 pF

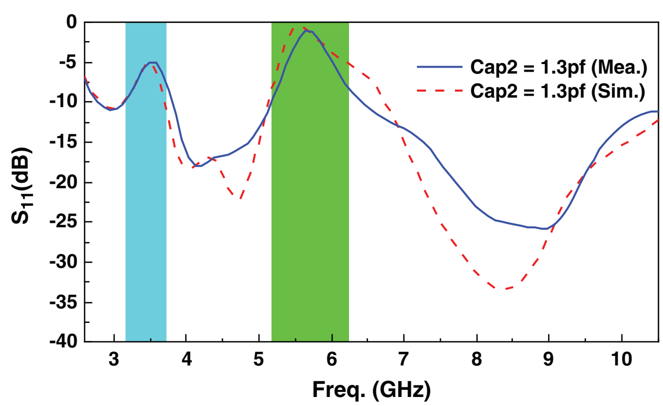

Figure 4: S11 response of the tunable WLAN notched UWB antenna having cap2 = 1.3 pF

The radiation attributes of the proposed tunable WLAN notched UWB antenna at cap2 = 0.1 pF is also simulated in Ansoft HFSS and is provided in Fig. 5. The corresponding radiation patterns at lower (4.1 GHz), mid (6.1 GHz), and higher (9.1 GHz) frequency range are shown in

Figs. 5a–5c, respectively. It is noticed that the proposed tunable WLAN notched UWB antenna radiation pattern is deteriorating while shifting from lower to higher frequencies, which is due to the higher-order harmonics generation. It got a typical dumb-bell shaped in the corresponding E-plane, while an omnidirectional pattern in the subsequent H-plane.

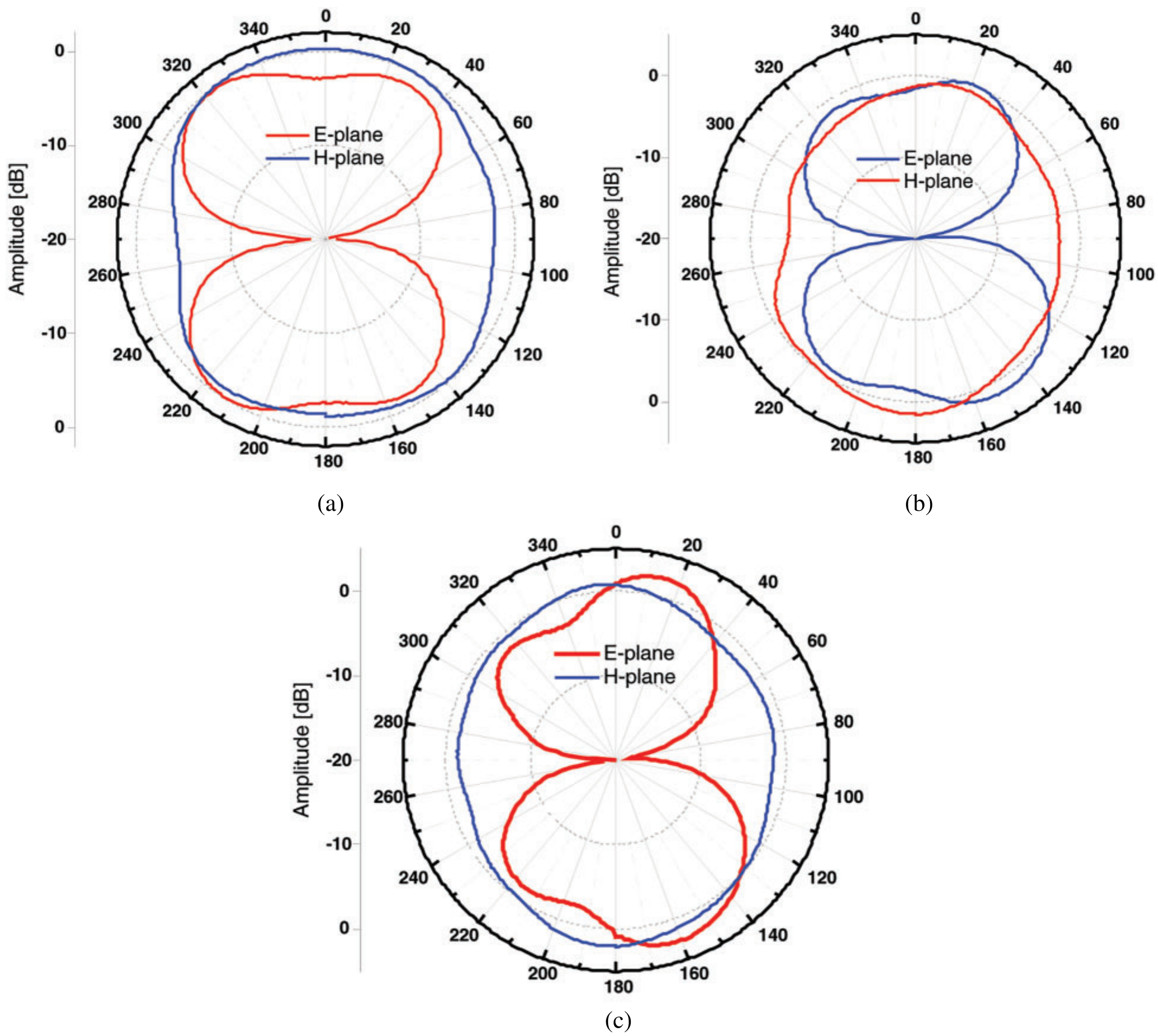

Figure 5: Simulated radiation pattern tunable WLAN notched UWB at frequencies; (a) 4.1 GHz; (b) 6.1 GHz, (c) 9.1 GHz

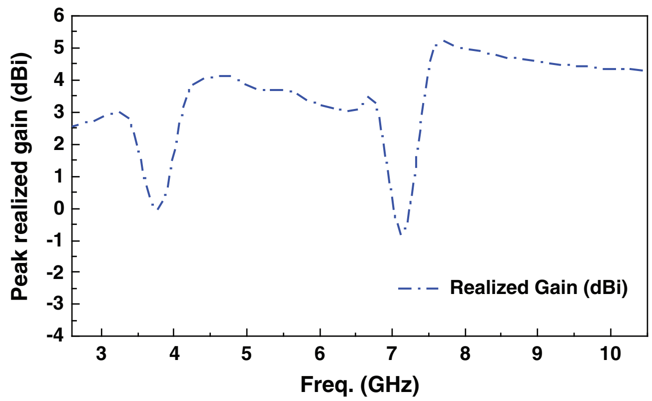

Figure 6: Simulated realized gain of the proposed tunable WLAN notched UWB antenna at cap2 = 0.1 pF

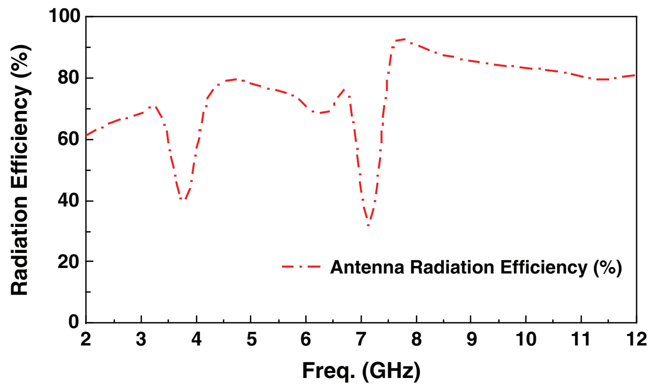

Figure 7: Simulated antenna radiation efficiency (%) of the proposed tunable WLAN notched UWB antenna at cap2 = 1.3 pF

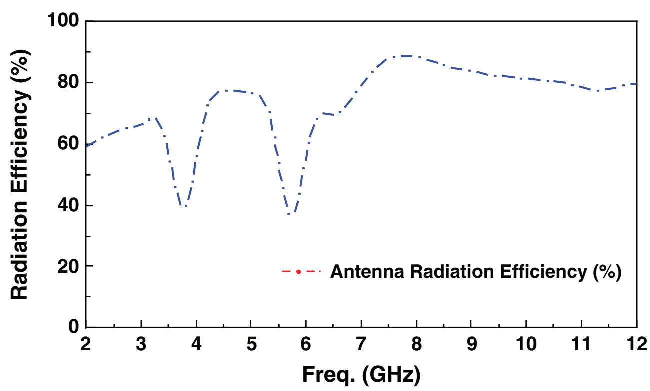

Figure 8: Simulated antenna radiation efficiency (%) of the proposed tunable WLAN notched UWB antenna at cap2 = 0.1 pF

The simulated peak realized gain (dBi) of the proposed tunable WLAN notched UWB antenna at cap2 = 0.1 pF is also simulated and is shown in Fig. 6. It is noticed that the antenna possesses an acceptable realized gain in passband while a suppression due to destructive interference at the notched bands. Fig. 7 demonstrates the simulated percentage radiation efficiency of the proposed antenna at cap2 = 0.1 pF. It is seen that the antenna has an acceptable radiation efficiency in the passband with good suppression within the notched frequency bands. Fig. 8 illustrates the simulated radiation efficiency of the proposed antenna at cap2 = 1.3 pF. It is clear from Figs. 7 and 8 that the corresponding WiMAX band notch is fixed while the WLAN band can be adjusted accordingly to the application. The simulated gain and radiation plots further support our proposed claims.

5 Conclusion

We presented a compact wideband tunable WLAN notched antenna with a fixed WiMAX notched band. The proposed tunable WLAN notched UWB antenna uses a simple slot resonator placed in the main radiator of the antenna for fixed WiMAX band notch, while inverted L-shaped capacitors integrated resonator in the partial ground plane for controllable WLAN notched band. These integrated variable capacitors are responsible for the wide tuning of WLAN notch from 7.1 GHz to 5.45 GHz with corresponding capacitor values from 0.1 pF to 1.3 pF. The antenna possesses the capability to tune the WLAN notch band from the upper WLAN to the lower WLAN band, which is quite promising. The proposed antenna is advantageous and has the flexibility to adjust according to the device requirements. It will be one of the possible candidates to be utilized in overlay cognitive radio UWB applications and URLLC service in 5G tactile internet.

Funding Statement: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIT) (No. 2019R1A4A1023746, No. 2019R1F1A1060799) and the Strengthening R&D Capability Program of Sejong University.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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