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RESEARCH ARTICLE-ELECTRICAL ENGINEERING

A PIN Diode-Enabled Compact Size Antenna for Transition Between UWB and Notched UWB Modes

Musa Hussain[1] · Wahaj Abbas Awan[2] · Abdullah Alwabli[3] · Amar Y. Jaffar[4] · Wesam N. Eid[5] · Ayman A. Althuwayb[6]

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Abstract
This article presents a miniaturized antenna operating on ultra-wideband (UWB) spectrum having two reconfigurable notch bands. Initially, an antenna is designed for UWB applications, offering a 3.3–14.5 GHz impedance bandwidth. Subsequently, a semicircular stub and an arc-shaped slot are etched to achieve two distinguish notch bands at 3.7 and 8.1 GHz. PIN diodes are loaded onto the antenna to enable on-demand switching between notch bands. The final geometry of the antenna offers compact size of 15 mm × 20 mm × 1.6 mm and is designed using commercially available substrate material FR-4. The structure of antenna consists of a rectangular stub loaded into a circular patch, while an additional semicircular stub and arc-shaped slot are utilized to achieve notch bands. The antenna provides a moderate value of gain surpassing 2.5 dBi in the operational region. The antenna has the capability to operate between the UWB mode or the UWB mode having single or dual notch bands using two PIN diodes. To validate the simulated results, a hardware prototype of the design is fabricated and tested, yielding similar results obtained from software-based antenna. Finally, the antenna performance is compared with recently reported similar work in literature, demonstrating advantages such as miniaturization, wideband, moderate gain, and high efficiency along with on-demand switching characteristics while maintaining simple geometrical configuration. These characteristics highlight the scientific contribution of the proposed work along with making it a potential candidate for targeted applications.

Keywords Miniaturized antenna · Notch band · Reconfiguration · UWB · Portable electronics

1 Introduction

Due to its several advantages, the ultra-wideband (UWB) gets recognition in academic research and industrial area as well. One main and key merit of UWB antenna is providing large data rate, which is fundamental demand of 5G and 6G technologies. Other advantages include low spectral power density, easy to fabricate, low fabrication cost and high operation capability [1, 2]. According to FCC (Federal Communication Commission), UWB ranges from 3.1 to 10.6 GHz. Due to superior unlicensed bands, UWB technology provides higher data rates in short-range communication such as IOT, RFID, and WBANs (Wireless Body Area Networks) and bio-medical applications [3–5].

Ultra-wideband provides many applications in wireless communications, but due to wideband, the interference happens [6, 7]. This interference is due to newly occupied band spectrum for 5G sub-6GHz, or certain previously allocated bands of WiMAX, WLAN, and C band ranging from 3.3–3.7 GHz, 5.15–5.82 GHz and 7.1–7.9 GHz, accordingly [8]. The filters were used initially to stop specific bands while allowing others to pass [9–11]. However, as the devices are getting compact, the filters are not an effective way to embed along with antenna [12, 13]. Thus, to avoid interference, a notch band characteristic is introduced to filter unwanted or undesired frequency band from operational region [14]. A notch band antenna is designed by loading stubs, etching slots, or introducing meta-materials and DGS to get notch band along various frequencies. This interference can be obtained by introducing filters, which may bring complexity, boast size and cost of manufacturing increased [15–17].

To make communication model more intelligent, reconfigurability attribute is inaugurated in antenna system [18]. Due to this attribute, antenna system can switch mode of operation as per requirements. The reconfiguration is performed by

Extended author information available on the last page of the article

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adding PIN diodes, varactor diodes, meta-materials, and resonators [19–21]. The reconfiguration can also be achieved by modifying antenna structure and adding capacitor as in [22]. The split ring resonator (SRR) is also widely used to get reconfiguration of notch band in UWB antenna, which may bring complexity in design [23].

In literature, many works are performed to design antenna to operate over ultra-wideband and make it functional for notch band along with reconfiguration. The most widely used mechanism for reconfiguration is placing PIN diodes [24–26]. Besides reconfigurable antennas, some other types operating over multiple frequency bands [27], wideband [28] and highly efficient antenna [29] are also proposed in literature. In this literature survey, notch band antenna without reconfiguration as well as with reconfiguration is studied. The system elaborates the positives and negatives of this work. In last the suggested design novelty will be highlighted with paper layout.

A dual notch band antenna exhibits a high peak gain of 8 dBi and operates on notch bands of 1.7–2.69 GHz and 3.35–3.6 GHz is given in [30]. This work is good to offers dual notch band and high gain but has lack of reconfigurability. Another setback of this work is large dimensions of 58.7 mm × 58.7 mm with complex geometry. Another notch band antenna offering 3.3–3.8 GHz and 5.2–5.7 GHz is suggested in [31]. The antenna offers good value of gain around 5.5 dBi and has overall geometry of 33 mm × 32 mm × 1.5 mm. The demerit of this design is also complicated structure. A simplified structural antenna is reported in [32], which offers gain of 5.5 dBi and notch bands along 2–2.7 GHz and 3.45–3.8 GHz. This design work has demerit of large size of 45 mm × 35 mm. An antenna having measurement of 30 mm × 30 mm × 1.524 mm is presented in [33]. The antenna provides dual notch band at WiMAX and WLAN frequency. This work also has a lack of reconfigurability.

The frequency reconfigurable of notch band are given in [34–36]. In [34], a notch band is obtained by turning ON/OFF one PIN diode at 0.6–1.6 GHz. The antenna has high gain and size of 30 mm × 40 mm. The demerit of this design includes notch band functionality over only one band. A dual notch band antenna is given in [35], which offers notching at 3.7–3.8 GHz and 4–6.7 GHz. The notch bands are obtained by using diodes but cover very narrow and unspecified bands. Additionally, the dimension of design is also huge as compared to other work presented in literature. A single notch band is reported in [36], offering notch at 5–6.2 GHz. The antenna design has setback of single notch band operation and complex structure.

In addition, literature also contains various compact and printed antenna designs operating on UWB and offers multiple notch bands. These antenna performance and results are obtained by fractal geometries [37], its MIMO configuration [38] or my placement of EBGs structures [39]. In [37], a compact printed antenna is presented for WLAN and WiMAX applications. The antenna contains simplified fractal geometry and offers quadruple notch characteristics. The reported work offers notches at 3.5 GHz, 5.2 GHz, 5.5 GHz and 5.8 GHz. Another compact antenna is reported in [38], which offers UWB along with notch bands. This work has an impedance bandwidth of 3.0–11.1 GHz and contains a 2 element MIMO antenna.

It is analyzed and concluded from the above literature survey that some designs offer wide band rejection but have complex size or large geometry. Some design has lack of reconfiguration while others offer notch reconfigurability over single band switching. This analysis shows that there is still need for research to design an antenna having reconfigurable notch bands, with small size and simple geometry as well as moderate value of gain. The antenna suggested in this manuscript has below advantages and novelty:

- Small, simplified structure
- Operating over UWB
- Reconfigurable Notch Band
- Filter complete band of frequency
- Moderate gain

The remaining paper is divided into five sections, and the designing technique and principle of working for suggested work are explained in the second section. The hardware prototype, measurement, and comparison between tested and software generated results are given in the third section of the article. The detailed contrast between this work and recently published work is provided in the last section, and the suggested work is concluded following the references.

2 Antenna Designing

The geometrical structure of the suggested design has a circular-shaped patch and CPW (Co-Planar Waveguide) microstrip feedline, as illustrated in Fig. 1. The structure of antenna also has rectangular-shaped stub and semicircular ring-shaped stub as well as arc-shaped slot. To obtain the reconfiguration, two PIN diodes are loaded to antenna. The design is embedded on the rear side of well-known substrate material FR-4 having overall size of $T_1 \times J_1 \times H = 15$ mm × 20 mm × 1.6 mm. The utilized dielectric material has relative permittivity and loss tangent of 0.02. The structure of antenna is constructed, and performance of design is analyzed by using EM (electromagnetic) software tool CST.

2.1 Design Methodology

Various steps involved in designing the recommended dual notch ultra-wideband reconfigurable antenna are depicted in

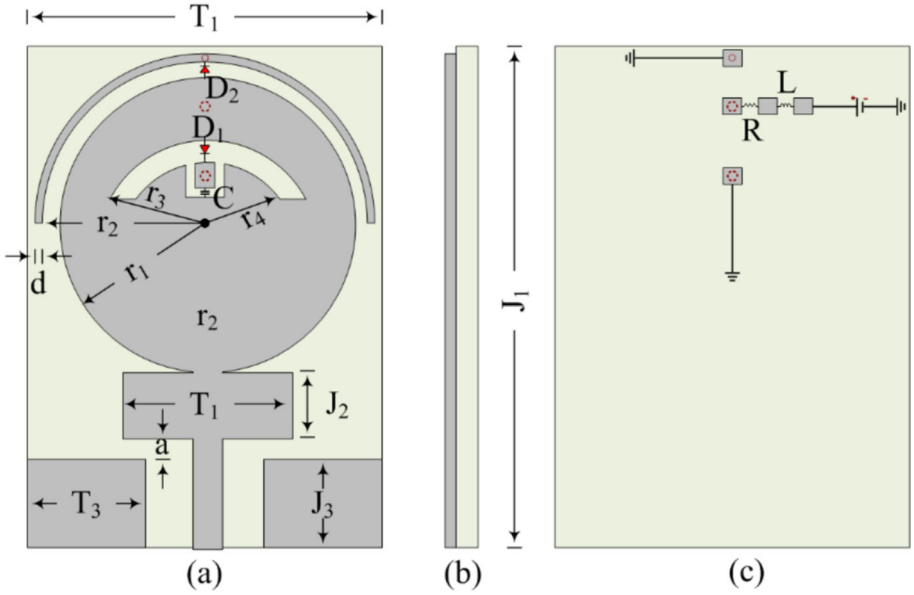

Fig. 1 **a** Top side of proposed CPW feed antenna **b** Side view **c** back view of proposed antenna

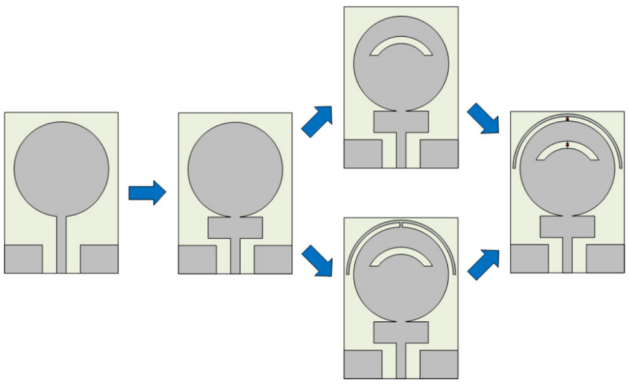

Fig. 2 Design stages of proposed UWB notch band reconfigurable antenna

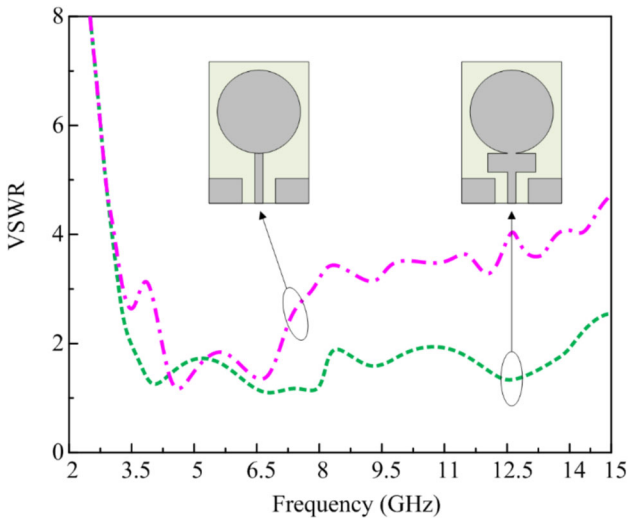

Fig. 3 Design and analysis of construction of UWB antenna from circular patch monopole antenna

Fig. 2. It can be seen from the figure that the circular patch antenna having CPW feedline is constructed in first step. The radius of the circular patch (r_1) is calculated by using the circular patch antenna equations referred to in [40, 41]. In the second stage of design, the rectangular stub is loaded to antenna between circular-shaped patch and feedline. This step results in improvement of the operational bandwidth, as the electrical length of antenna is increased. In the third stage of designing, the single and double notch are achieved. It can be observed that when the arc-shaped slot is etched from antenna, the single notch band at 8 GHz is obtained. To obtain the dual notches, the semicircular stub is placed to the top side of circular patch antenna. The resultant design offers two notches at 8.1 GHz and 3.6 GHz. The PIN diode is embedded at the edges of the arc-shaped slot and between semicircular stub and circular patch to get reconfigurable notch bands.

2.2 Design of UWB Antenna

As it is discussed in Sect. 2.1, the ultra-wideband is obtained after loading the rectangular-shaped stub between circular patch and feedline. The simulated VSWR of both circular patch antenna and stub loaded antenna is provided in Fig. 3. It can be noticed from the given figure that the circular patch monopole antenna offers VSWR value below 2, ranging from 3.6 to 6.8 GHz. The second graph in the figure expresses the VSWR of rectangular stub loaded circular patch monopole antenna. The loading of the rectangular stub is the second step of designing of proposed antenna, where the electrical length

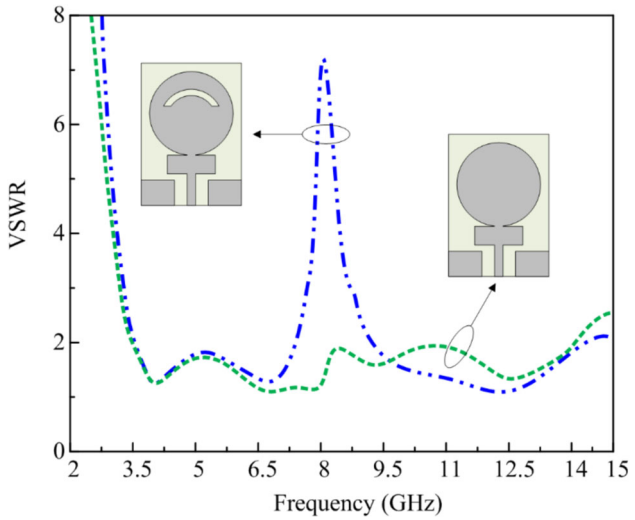

Fig. 4 Design and analysis of construction of single notch band antenna from UWB antenna

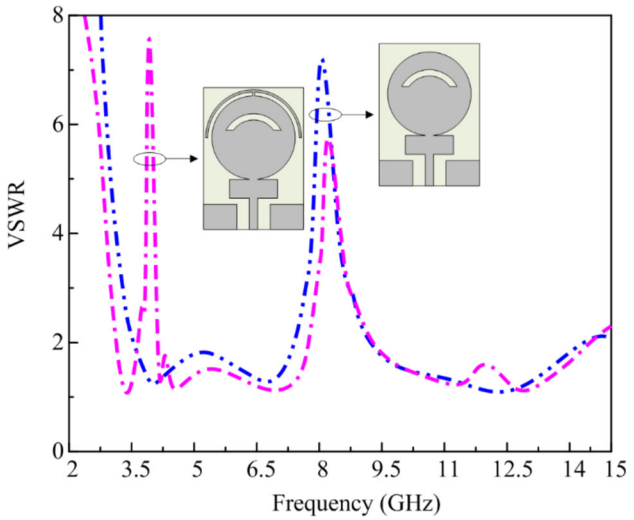

Fig. 5 Design and analysis of construction of double notch bands antenna from single notch band antenna

of antenna increased, which in result enhances the operational bandwidth. The length and width of the rectangular stub are obtained after following various parametric analysis. At the optimal value, the antenna offers perfect impedance matching along with ultra-wideband. The antenna provides bandwidth of 10.2 GHz ranging from 3.3 to 14.5 GHz.

2.3 UWB with Single Notch

The antenna operating at UWB region has many applications and advantages of low complexity, low cost, high data rate, high data transmission rate, low interference, and low spectral density [42]. For notch band antenna, the placement of the notching structure in the antenna element in order to mitigate the existing sub-bands is one of the most important and crucial challenges [43]. In this design, the arc-shaped slot is etched from the antenna to eliminate the sub-band from operating UWB spectrum. It can be seen from Fig. 4 that the arc-shaped slot is etched from the circular patch antenna to get the notch band along 8.1 GHz. The dimension of the slot is estimated from the below equation, while the position of the slot is obtained after performing various parametric analysis. It can also be noticed from the figure that the etching of the slot does not introduce any complexity to the design. The resultant antenna offers a single notch band of 2.75 GHz ranging from 6.75 to 9.5 GHz.

$$f\text{notch} = \frac{c}{X \times \text{Leff} \times \sqrt{\epsilon\text{eff}}}$$

In the above equation, f_{notch} represents the central frequency of slot, c shows the speed of light, effective length is given by Leff, and dielectric constant by ε_{eff}. X is a multiple factor, which refers to the region of the wavelength.

2.4 UWB with Dual Notch

The second notch band is obtained after loading semicircular-shaped stub at the top side of circular patch antenna. The dimensions and location of the stub is calculated by carrying various parametric analysis. VSWR comparison between antenna having slot only offering single notch and antenna width slot and stub offering double notches is given in Fig. 5. It can be noticed that after loading the semicircular-shaped stub, the additional notch is obtained at 3.7 GHz, with no impact on the UWB operation. The antenna after this step offers double notch bands at 3.7 GHz ranging 3.5–3.8 GHz, and 8.1 GHz ranging from 6.75 to 9 GHz.

2.5 UWB Antenna with Reconfigurable Notch Band

It is clear from the above sections that the suggested design is capable of offering UWB spectrum along with single and double notch bands. However, the ability to control the outcomes of antenna is important and challenging. The antenna with no arc-shaped stub and semicircular slot operates at UWB, while antenna with stub offers single notch as well as dual notch bands are obtained after loading slot. For modern and forthcoming communication models, only antenna operating at UWB and offering notch band are not competitive; therefore, independent controllable notched UWB antennas are the key requirements for modern communication technologies.

In this work, the PIN diodes are utilized to get the configuration, which has advantages of small size and switching response. The electrical length of the patch and ground plane of the antenna change the flow of current, which depends on the state of the diode loaded. After loading the diode to

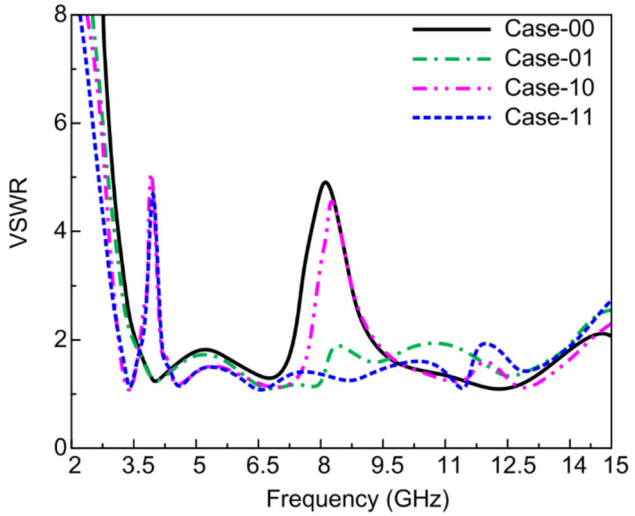

Fig. 6 Design and analysis of construction of reconfigurable dual notch bands antenna

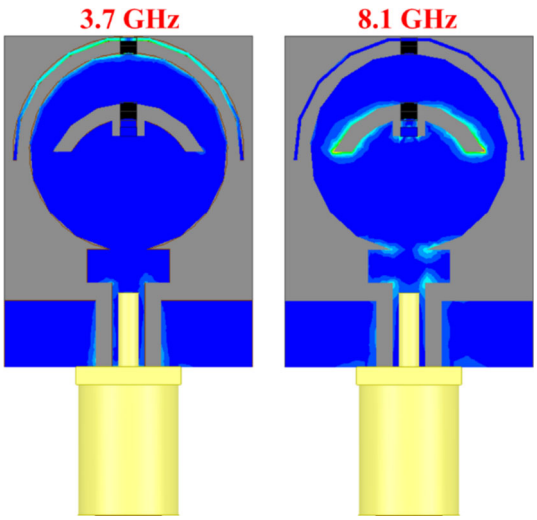

Fig. 7 Surface current distribution of proposed antenna at notch bands of 3.7 GHz and 8.1 GHz

the recommended antenna structure, the lumped resistance-capacitor-inductor (RLC) and its values are given in [33]. Furthermore, to change the patch of current flow, a DC block 1 pF capacitor is utilized. The padding and vias are introduced to the antenna to get accurate results.

In Fig. 6, the simulated value of the VSWR is given at various states of the diodes. It can be seen from the given figure that when both diodes are in OFF state (case-00), the antenna offers single notch band at 8.1 GHz, whereas when both diodes are in ON state (case-11), the notch band along 3.7 GHz is obtained. This can also be examined from the figure that when D_1 is On and D_2 is OFF (case-10), the dual notches are obtained. To get UWB spectrum, the D_1 should be OFF and D_2 is ON expressing case-01. The outcomes of various switching conditions are given in Fig. 6, and more detailed discussion about the results is presented in forthcoming section. It is worthy to note that addition of the biasing circuit slightly shifted the notch bands which are optimized by using the parametric analysis to get desire bands.

To analyze the antenna efficiency of the notch structure, the surface current distribution provides better understanding. Figure 7 shows the surface current distribution of proposed at notch bands of 3.7 GHz and 8.1 GHz. For 3.7 GHz, it can be seen from the figure that current is mostly at the upper semicircular stub, whereas for 8.1 GHz, mostly current flow is observed at the edges of the arc-shaped slot. It is also clear from the previous sections that semicircular stub is loaded to get the first notch along 3.7 GHz and slot is etched to get the second notch at 8.1 GHz.

3 Results and Discussion

3.1 Fabrication and Measurement Setup

The proposed antenna is designed, simulated, and optimized by using electromagnetic (EM) solver HFSS (high-frequency structure simulator). The use for this EM solver has advantages of providing precise and consistent results of most complex EM models, and it also reduces the number of tests and verification required. In addition, it also avoids the construction of multiple prototypes, which reduces time and production cost.

To verify and validate the simulated results obtained by HFSS tool, the antenna prototype is fabricated, as given in Fig. 8. The antenna contains the diodes which are used for switching to different states of operation. The complete biasing circuit and connection of wires are given to show the operation of diodes to get reconfiguration. The near field analysis is performed by utilizing the vector network analyzer (VNA), while far field measurement is performed in isolated RF anechoic chamber.

3.2 VSWR of Various Cases

The VSWR results of the proposed design are divided into two cases based on antenna operation. In the first case, the antenna offers UWB band along with dual notch band. In the second case, the antenna offers UWB along with single notch band. This division in results brings better comparison and avoids complexity from the graphs.

Case 1: In this case, the antenna is analyzed when first D_1 is ON and D_2 is OFF (state 10), and secondly D_1 is OFF and D_2 is ON (state 01). It can be seen from the figure that

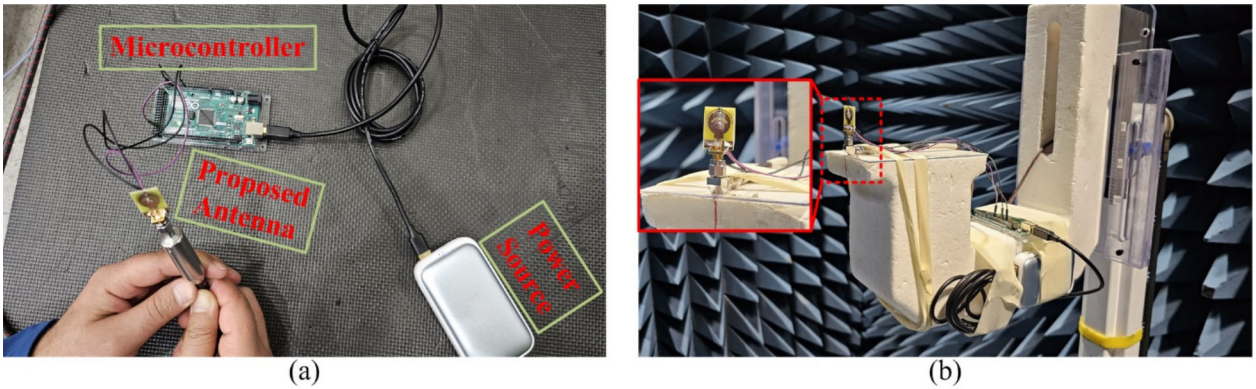

Fig. 8 Fabricated prototype and measurement setup **a** VSWR **b** Far-field

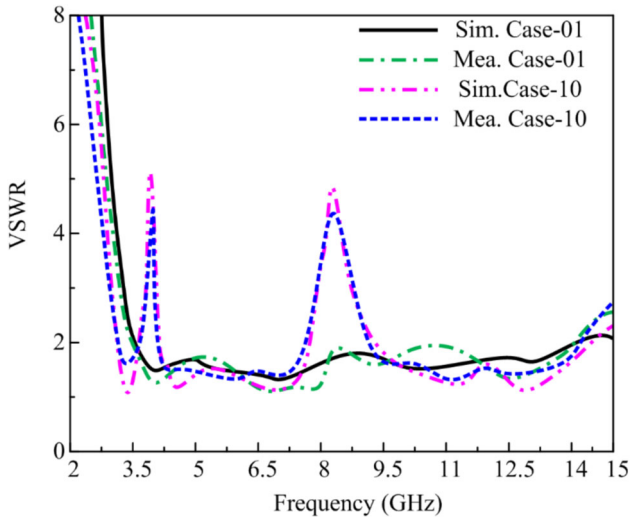

Fig. 9 VSWR plot of antenna offering UWB and dual notch band at state 01 and state 10

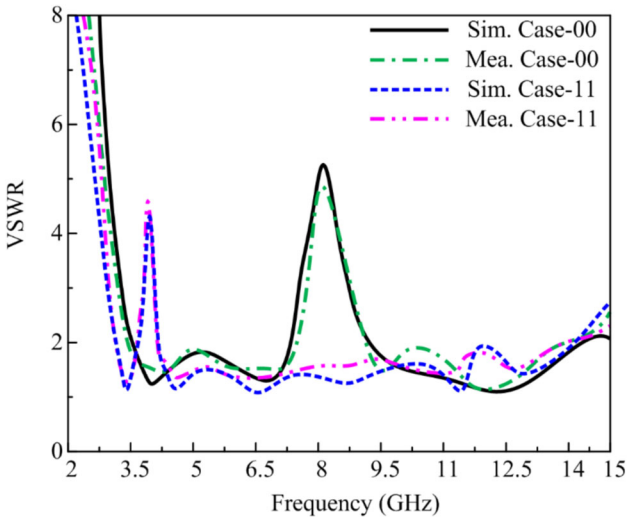

Fig. 10 VSWR plot of antenna offering single notch band at state 00 and state 11

when diode D_1 is ON and D_2 is OFF, the antenna offers dual notch band along 3.7 GHz / 8.1 GHz ranging from 3.5–3.8 GHz/6.75–9 GHz, respectively. Alternatively, when the D_1 is switched OFF and D_2 is switched ON, the antenna offers UWB spectrum 3.3–14.5 GHz, as given in Fig. 9. It can also be noticed from the plot that simulated results are quite similar to measured results. The minor and negligible distortion is observed, which is may due to personal error.

Case 2: In this case, the antenna is analyzed when both of the diode is switch OFF (state 00), and secondly when both diodes are switch ON (state 11). It can be seen from the figure that, when diode D_1 and D_2 are switched OFF, the antenna offers single notch band at 8.1 GHz with bandwidth ranging from 6.75 to 9 GHz. Similarly, when the D_1 and D_2 are switched ON, the antenna offers single notch band at 3.6 GHz having bandwidth ranging from 3.5 to 3.8 GHz, as given in Fig. 10. The depicted figure also expresses the resemblance between tested and simulated results. The minor distortion is noted in results which are due to personal human error.

3.3 Radiation Pattern

Figure 11 represents the measured and predicted radiation pattern of proposed dual notch ultra-wideband antenna at three different resonance frequencies of 3.3 GHz, 6.5 GHz, and 11 GHz. This is noteworthy that the antenna pattern is analyzed in E-plane (where $\theta = 0°$) and H-plane (where $\theta = 90°$). At 3.3 GHz, this work offers bi-directional radiation pattern in the E-plane and omni-directional pattern in the H-plane. At the resonance frequency of 6.5 GHz, the antenna offers an omni-directional pattern at H-plane but nearly bi-directional in E-plane. At the third frequency of 11 GHz, the omni-directional and bi-directional pattern in the H- and E-plane is distorted. This effect on the pattern is due to the operation in higher band as well as the effect of slot and diode loading to antenna. Moreover, the comparison between simulated and tested radiation pattern is also provided in figure. It is concluded that antenna measured and simulated radiation pattern are similar.

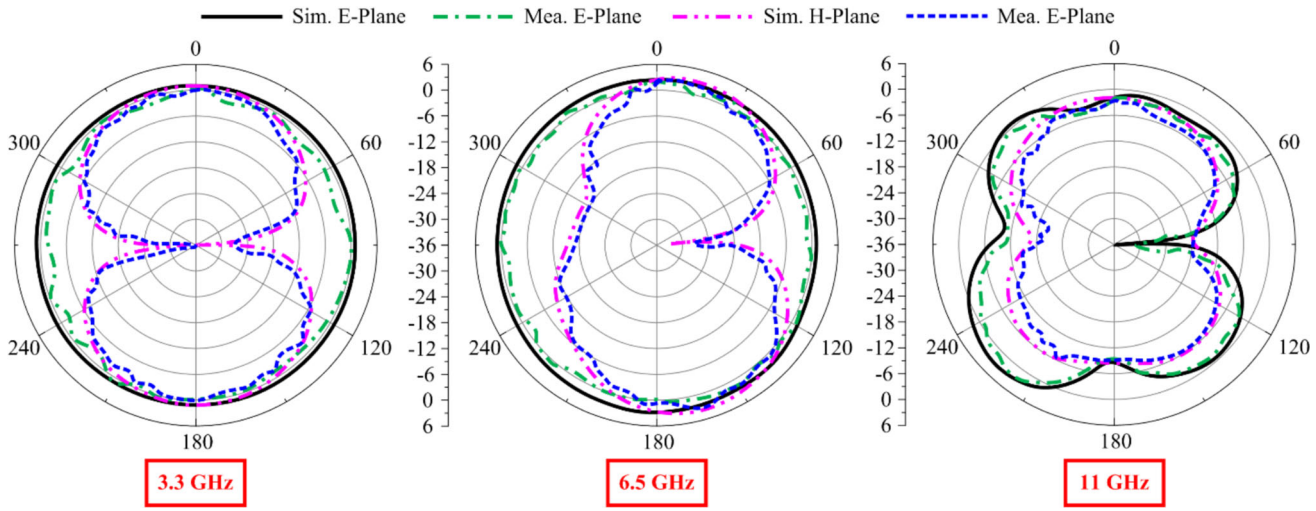

Fig. 11 Radiation pattern of proposed antenna at different resonance frequency

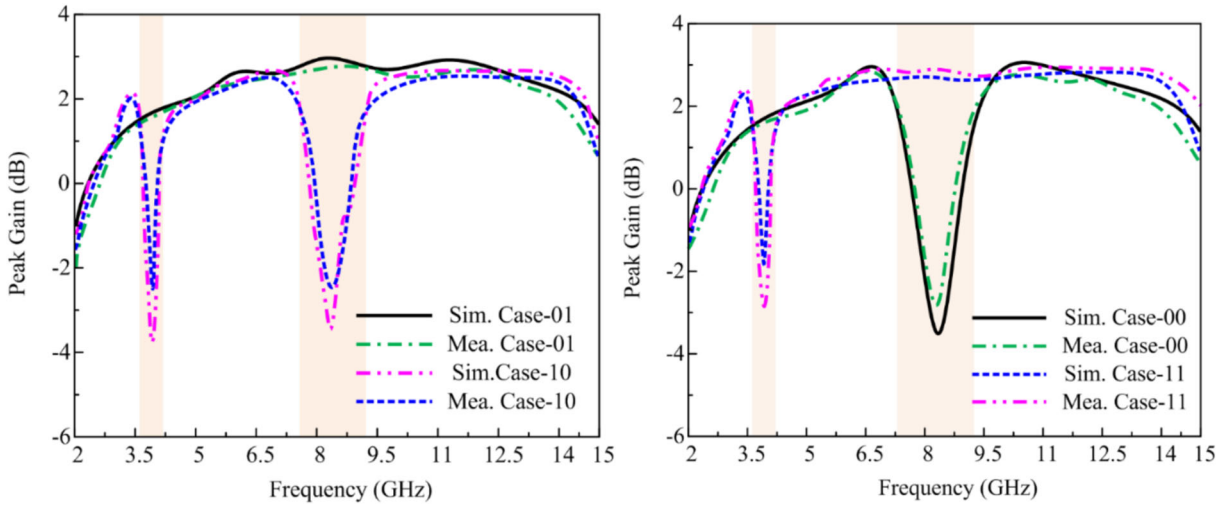

Fig. 12 Gain of proposed antenna **a** at UWB and dual notch band **b** at single notch band

3.4 Gain and Efficiency

Figure 12 provides the comparison between tested and predicated peak gain of recommended dual notch UWB antenna. It can be seen that at case-01, where D_1 is OFF and D_2 is ON, the antenna operates at ultra-wideband and offers gain of > 2.35 dBi at operational band spectrum of 3.3–14.5 GHz, with maximum value of 2.45 dBi at 8.1 GHz. When the D_1 is ON and D_2 is OFF referring to case-10, the antenna offers dual notch band at 3.7 GHz and 8.1 GHz, where the antenna offers negative value of gain –3.8 dBi and 3.7 dBi, respectively. At this case, the antenna offers moderate value of gain around 2.2 dBi in operational band spectrum, other than notch region.

When both of the diodes are switched OFF (case-00), the antenna offers a single notch along 8.1 GHz. In this region of notch band, the antenna offers gain around –3.9 dBi, whereas other than notch region, the antenna offers gain value of 2.25 dBi. In the last case, where both diodes are ON (case-11), the antenna offers negative gain of –3.82 dBi at 3.7 GHz. Besides the notching region, the value of gain remains stable and moderate and provides gain of > 2.25 dBi. The comparison of antenna gain at operational region and notch band region is given in Fig. 12 along with comparison with gain obtained from prototype.

Figure 13 represents the radiation efficiency of this antenna in four switching cases. It can be seen that antenna offers radiation efficiency > 95% along operational region for case-01, where antenna operates at UWB. In case-10, where antenna offers two notch band, the radiation efficiency is > 88% at operational region, while minimum value of efficiency is observed at 30% and 32% at notch band of 3.7 GHz and 8.1 GHz. For case-00, the antenna offers efficiency of 88% in operational region, while least value of 40% at notch

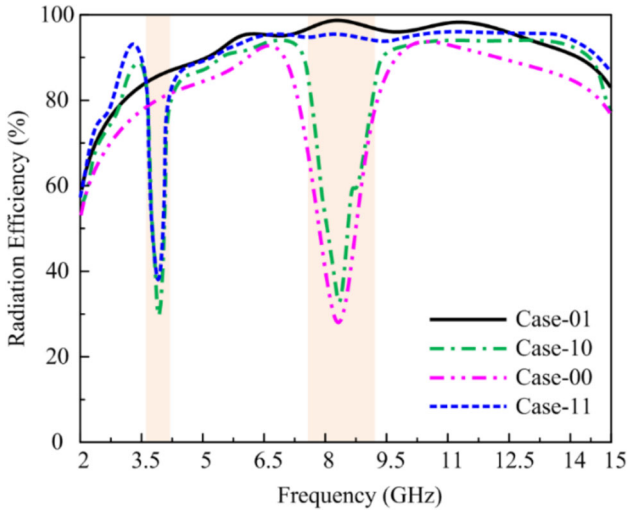

Fig. 13 Radiation efficiency of proposed antenna at various switching states

band of 8.1 GHz. Similarly, in case-11, the antenna offers a single notch band along 3.7 GHz, where the value of radiation efficiency is 40% and 90% in the rest of the operational region. It is clear that the value of efficiency decreases at the notch band (Table 1).

4 Comparison with Literary Works

Table 2 represents the comparison between proposed antenna performance parameters, and already published antenna performance parameters. The performances of antenna are compared in terms of operational bandwidth, notching bandwidth, and value of peak gain. It can be seen that the proposed antenna offers compact size as compared to the rest of the antenna having an additional feature of simplified geometrical configuration. The antenna also offers ultra-wideband as compared to other published ones with wide notching bandwidth which can be controlled easily. Although the value of gain of proposed antenna is moderate and comparatively lower than the work reported in [20–22], they have the disadvantage of lower bandwidth along with no reconfigurability. On the other hand, the work reported in [24–26] has the reconfigurability feature but either their size is too big, or they have limited bandwidth. Thus, the comparison further validated the performance of the antenna and made it a potential candidate for the application requiring compact size antenna having ultra-widebandwidth and on-demand notch band feature.

Table 1 Comparison between outcomes of antenna at various switching states

State	Antenna Performance	Bandwidth (GHz)	Peak Gain (dBi)	Efficiency (%)
10	Dual Notch	3.3–3.5 / 3.8–6.75 / 9.5–14.5	2.2	90
01	UWB	3.3–14.5	2.5	95
11	Single Notch	3.3–3.5/3.8–14.5	2.45	92
00	Single Notch	3.3–6.75/9.5–14.5	2.3	88

Table 2 Comparison between proposed work and already published work

Ref	Dimensions ($\lambda \times \lambda$)	Operational bandwidth (GHz)	Notching bandwidth (GHz)	Peak gain (dBi)	Notch band	Reconfigurable
[27]	0.07 × 0.03	1.75–1.89 2.39–2.51 5.05–6.06	–	5.25	No	No
[28]	0.33 × 0.145	5.08–7.23	–	2.25	No	No
[29]	0.5 × 0.5	4.8–5.99	–	2.5	No	No
[30]	0.23 × 0.23	1.5–4	1.7–2.69/3.35–3.6	8	Yes	No
[31]	0.33 × 0.32	3–12	3.3–3.8/5.2–5.7	5.5	Yes	No
[32]	0.18 × 0.14	1.2–12.5	2–2.7/3.45–3.8	5.5	Yes	No
[33]	0.3 × 0.3	3–12	3.2–3.8/5.15–5.85	2.4	Yes	No
[34]	0.24 × 0.33	2–8	0.6–1.6	7	Yes	Yes
[35]	0.43 × 0.43	2–7	3.7–3.8/4–6.7	4.86	Yes	Yes
[36]	0.2 × 0.41	2–12	5–6.2	3.5	Yes	Yes
This work	0.16 × 0.22	3.3–14.5	3.5–3.8/6.75–9.5	2.5	Yes	Yes

5 Conclusion

This work presents the design and implementation of compact antenna operating on UWB and offering dual reconfigurable notches. First of all, the circular patch antenna was designed for microwave applications, where the rectangular stub is loaded to improve the return loss as well as the bandwidth of antenna. In the next step, an arc-shaped slot is etched from the circular patch antenna to get single notch band along 8.1 GHz. In the next stage of designing, a semicircular-shaped stub is loaded at the top of the patch, to get dual notch bands. The additional notch band was observed at 3.7 GHz. In the final stage, two pin diodes are loaded to antenna in order to achieve reconfiguration. The final geometry of antenna has many advantages in terms of compact size, simple geometry, operating at UWB and offering dual notch band. The antenna is able to operate either on UWB mode, or single notch band mode or dual notch band mode, depending on the state of diodes. The prototype is also fabricated and tested to verify the software generated results. Moreover, the comparison between hardware and software results shows performance stability. Furthermore, this work is also compared with the state of the artwork. The comparison with previous published work, results, and performance along with aforementioned features makes this design a strong candidate for future devices used in portable electronics, requiring compact size antenna having reconfigurable notch band feature while maintaining ultra-widebandwidth.

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Authors and Affiliations

Musa Hussain[1] · Wahaj Abbas Awan[2] · Abdullah Alwabli[3] · Amar Y. Jaffar[4] · Wesam N. Eid[5] · Ayman A. Althuwayb[6]

✉ Musa Hussain
musa.hussain@griffithuni.edu.au

Wahaj Abbas Awan
wahajabbasawan@chungbuk.ac.kr

Abdullah Alwabli
aswabli@uqu.edu.sa

Amar Y. Jaffar
ayjaafar@uqu.edu.sa

Wesam N. Eid
wneid@uqu.edu.sa

Ayman A. Althuwayb
aaalthuwayb@ju.edu.sa

[1] School of Engineering and Built Environment, Griffith University, Gold Coast Campus, Southport, QLD 4215, Australia

[2] Department of Information and Communication Engineering, Chungbuk National University, Cheongju 28644, South Korea

[3] Department of Electrical Engineering, College of Engineering and Computing in Al-Qunfudhah, Umm Al-Qura University, Mecca, Kingdom of Saudi Arabia

[4] Computer and Network Engineering Department, College of Computing, Umm Al-Qura University, Mecca, Kingdom of Saudi Arabia

[5] Cyber Security Department, College of Computing, Umm Al-Qura University, Mecca, Kingdom of Saudi Arabia

[6] Electrical Engineering Department, College of Engineering, Jouf University, Sakaka, Aljouf 72388, Kingdom of Saudi Arabia