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Triple Rectangular Notch UWB Antenna Using EBG and SRR

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ABSTRACT This paper investigates an ultra-wideband (UWB) antenna with a triple-rectangular notch band at 5G, WLAN, and Satellite downlink bands. The 5G and WLAN bands are notched by using a pair of electromagnetic bandgap (EBG) structures while the satellite downlink band is notched by using two split-ring resonators (SRRs). The EBG structure is a metallic conductor loaded on the backside of the radiator which is connected to the patch via a shorting pin. The SRRs consist of a pair of metallic rings etched on the backside of the feedline. The simulated and measured results show that the proposed antenna has an operational bandwidth from 3.1 – 11.8 GHz for $|S11| < -10$ rejecting 5G sub-6 GHz (3.4 – 3.9 GHz), WLAN (5.15 – 5.825 GHz), and satellite downlink band (7.25 – 7.75 GHz) signals with high selectivity. The peak gain of the UWB antenna is 3.86 dBi but it sharply decreases up to -13 dBi at stop-bands. The antenna also has additional advantages of the overall compact size ($20 \times 26 \times 1.52$ mm3) with stable gain and radiation patterns at the pass-bands.

INDEX TERMS Electromagnetic bandgap (EBG), notch-band antenna, rectangular notch, split ring resonators (SRR), triple-notch, UWB antenna.

I. INTRODUCTION

Since the spectrum of 3.1 – 10.6 GHz was released by FCC (Federal Communication Commission) for commercial applications, ultra-wideband (UWB) technology has its benefits like very low energy levels for short-range, high-information spread over a large bandwidth, usually more than 500 MHz. UWB is applicable in wireless positioning systems, biomedical imaging, sensor networks, and high data short-range communications [1]. However, UWB faces interference with coexisting narrow band communication systems. The antennas are the major source of communication systems. The design of the antennas with suitable characteristics, such as better impedance matching, stable radiations, compact size, and low cost are quite challenging. The microstrip patch antennas are good candidates for UWB applications because of their lightweight, planar geometry, and ease of integration with other electronic components [2]–[4].

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Existing license bands such as local-area networks (WLAN) (IEEE802.11a, HIPERLAN/2,) operating in the 5.15 – 5.825 GHz band, 5G sub-6 GHz (3.4 – 3.8 GHz), and X-band satellite communication (7.25 – 7.75 GHz) are offering the interference while designing UWB antennas. The efficient and economical way to solve this problem is to reject the interference at the front end of the UWB communication system.

A stopband is a band of frequencies through which a circuit, such as an EBG does not allow signals to pass through. Therefore, the UWB antenna with notching characteristics makes them more reliable [5]–[8]. Researchers developed many notched band UWB antennas using different approaches to negate interference problems. These band rejection techniques involve etching slots on the patch [9], [10], EBG structures [11]–[13], inserting a resonant cell in a microstrip line [14], and split-ring resonators [15], [16]. Some researchers achieved band-notched capabilities by coupling parasitic elements to the radiator [17], [18]. These techniques are capable of achieving

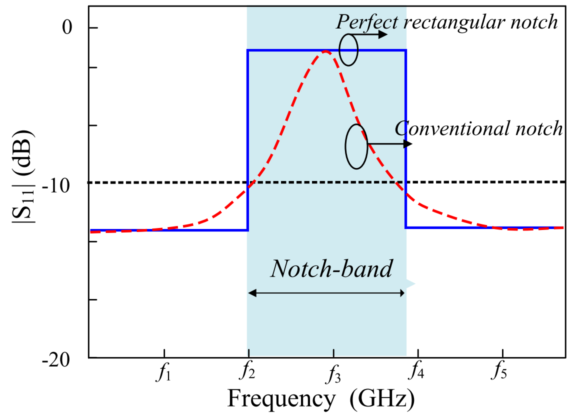

FIGURE 1. Demonstration of a conventional notch and rectangular notch.

highly efficient notch band designs. However, the techniques of coupling parasitic elements and etching slots may greatly affect the current distribution of pass-band frequencies, this may affect the pass-band radiation patterns.

However, the above mention techniques have a common drawback of the conventional notch with poor selectivity. The conventional notch which can stop interference with poor selectivity is not suitable for rejecting wide interference bands, such as the WLAN band having a bandwidth of 1 GHz. This gets more attention to design UWB antennas with sharp rejection characteristics. To undo the interference offered by unwanted bands practically, a rectangular notch with high selectivity is required. Figure 1 depicts a typical conventional and rectangular notch band. In recent years, a few rectangular notched antennas are reported because of their potential to reject the unwanted bands with high selectivity [19]–[25]. In [20], two conventional notch bands were attained at 5.2 and 5.8 GHz to reject WLAN (5 – 6 GHz) without filtering the bandwidth between two bands. In [19], [25], a rectangular notch band antenna is presented at the WLAN band using EBG structures. The [21] adopts stepped slots as a radiator to realize rectangular notch characteristics at WLAN and satellite downlink bands. In [22], the antenna demonstrates a band-stop characteristic with high selectivity at the WLAN band using an inductive coupling scheme. In [23], by slitting an open-ended quarter-wavelength split slot and a split ring resonator on the feed line and again only the WLAN band is notched rectangularly. Moreover, two stopbands (3.3–3.8 GHz and 5.0–5.9 GHz) with wideband notch characteristics are achieved using parasitic strips embedded in the ground plane and the slit etched on the radiating patch [24]. In summary, all of the rectangular notch band UWB antennas are dual band. There is not a single tri-band rectangular notch UWB antenna.

This paper extends the proposed methodology presented [25], where a single rectangular notch was successfully designed at WLAN band. To avoid interference from already existed licensed bands within the UWB spectrum, antennas with multiple band rejecting characteristics are required. Therefore, this work focuses on a compact UWB

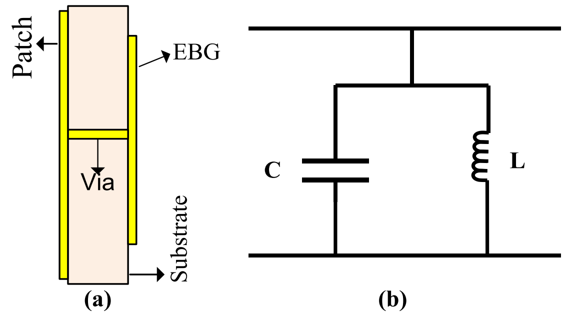

FIGURE 2. (a) single EBG structure (b) Equivalent circuit model.

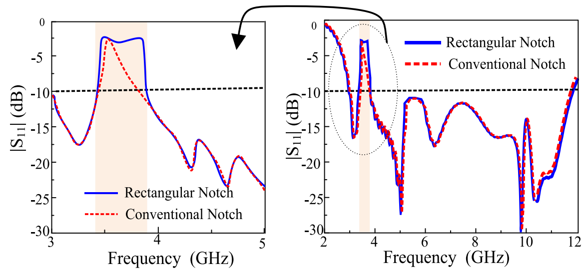

FIGURE 3. The simulated $|S_{11}|$ of UWB antenna with the conventional and rectangular notch at 5G band.

microstrip patch antenna with triple-rectangular notch bands to avoid interference. It is worth noting that the antenna presented in [25] uses only a pair of EBGs to realize a single rectangular notch band. However, this antenna uses two pairs of EBGs and a single pair of SRRs to realize triple rectangular notch bands within a limited size of the antenna. In this work, we proposed a triple rectangular notch UWB antenna at 5G sub-6 GHz, WLAN, and satellite downlink bands using EBGs and SRRs, which has stopped maximum interference offered by unwanted bands with high selectivity. It is noted that we need two EBGs or two SRRS to realize a single rectangular notch-band. To create multiple rectangular notches, several EBGs and SRRs are required. Therefore, it is quite challenging to achieve three rectangular notches within a limited space of the radiating patch. Moreover, during the literature review, we found that there is not a single UWB antenna with triple-rectangular notching characteristics. In the proposed design, at first, two EBGs are used to achieve a rectangular notch at 5G (3.4 – 3.9 GHz), and then two more EBGs are utilized to realize the rectangular notch at the WLAN (5.15 – 5.825 GHz) band, while two SRRs are responsible for the accomplishment of X-band (7.25 – 7.75 GHz) satellite downlink band rejection.

II. RECTANGULAR NOTCHED UWB ANTENNA

A simple patch is designed as a conventional antenna which is then fed by a coplanar waveguide with a characteristic impedance of 50 Ω using CST Microwave Studio. The lower ends of patch are truncated by a semicircle having radius *R*. The rectangular notches are achieved by using four EBG structures and two SRRs. The antenna is printed on Taconic

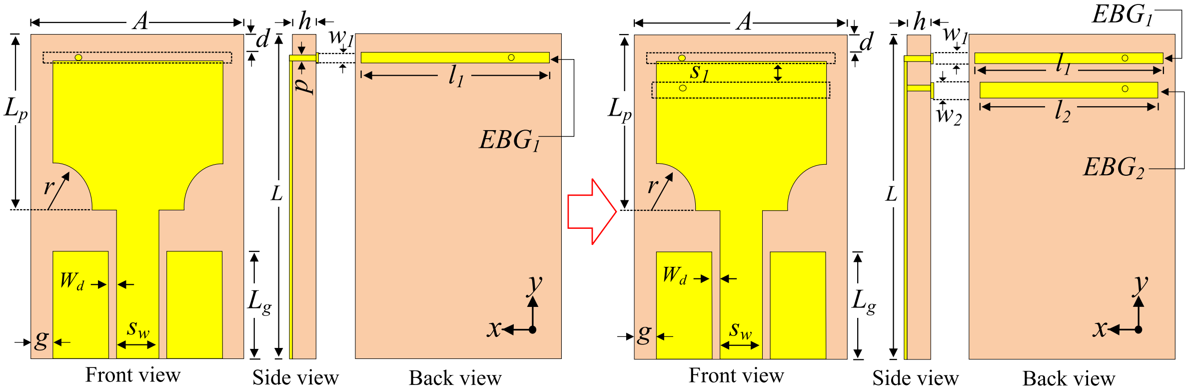

FIGURE 4. Rectangular notched UWB antenna from the conventional notch antenna.

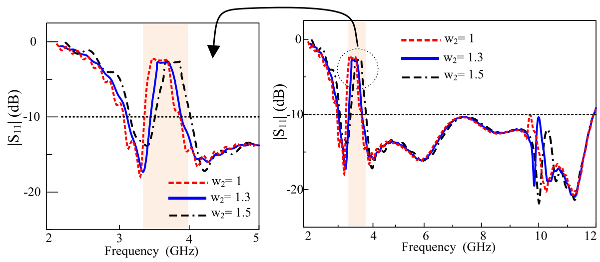

FIGURE 5. $|S_{11}|$ of the antenna for different values of w_2.

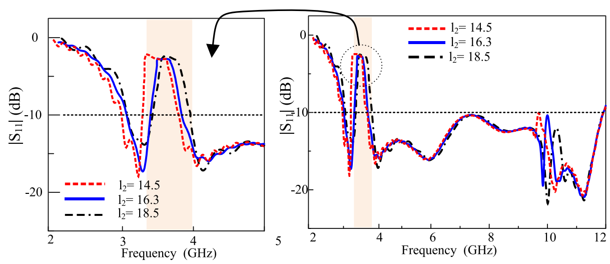

FIGURE 6. $|S_{11}|$ of the antenna for different values of l_2.

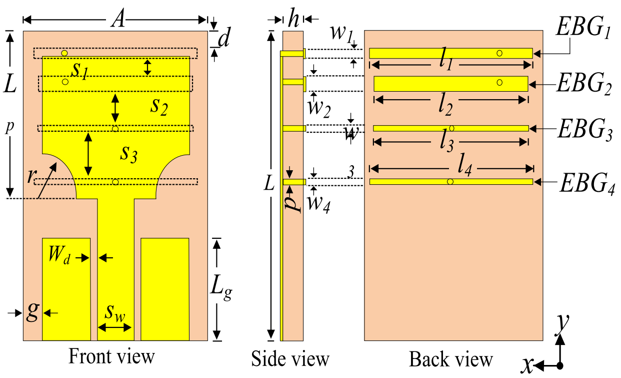

FIGURE 7. Geometry of the dual-band rectangular notch antenna.

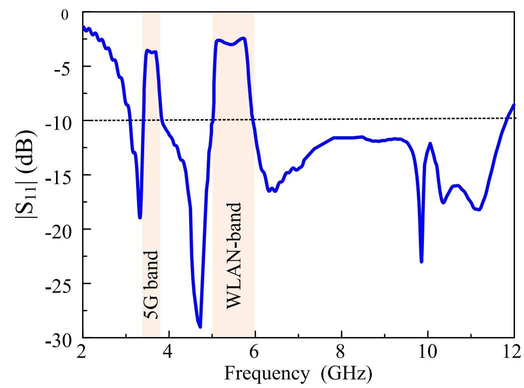

FIGURE 8. The $|S_{11}|$ characteristics of the antenna with 5G and WLAN band rejection.

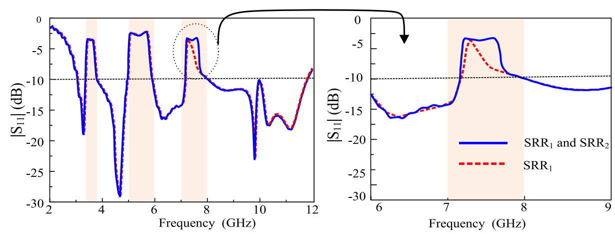

FIGURE 9. $|S_{11}|$ characteristics of the antenna for one and two SRRs.

TLY-5A substrate ($\varepsilon_r = 2.17$ and $\tan\delta = 0.0009$) with length L and width A. The optimized dimensions of the antenna are as follows: $A = 20$ mm, $L = 26$ mm, $h = 1.52$ mm, $L_g = 8.8$ mm, $L_p = 12$ mm, $r = 3.6$ mm, $S_w = 4.6$ mm, $W_d = 0.65$ mm, $l_1 = 18.25$ d mm, $l_2 = 17.5$ mm, $l_3 = 17.7$ mm,, $l_4 = 18.8$ mm, $w_1 = 0.8$ mm, $w_2 = 1.25$ mm, $w_3 = 0.4$ mm,, $w_4 = 0.4$ mm, $p = 0.2$ mm, $d = 1.6$ mm, $s_1 = 1.6$ mm, $s_2 = 2.75$ mm, $s_3 = 4$ mm, $g = 2$ mm, $x = 3.7$ mm, $x_1 = 3.8$ mm, $g = 0.3$ mm, $sv_1 = 1.67$ mm, $sv_2 = 1.2$, and $g_1 = 0.35$ mm.

A. 5G-BAND (3.4 – 3.8 GHz) REJECTION

The EBG structure is formed when a metal patch is connected to the radiating patch through a shorting pin, The EBG structure operates as a band stop filter, one EBG structure is enough to obtain a notched band. The metal patch can be characterized by LC resonators with the resonant frequency $f_r = \frac{1}{2\pi}\sqrt{LC}$. When an EBG is utilized, a narrow notch at

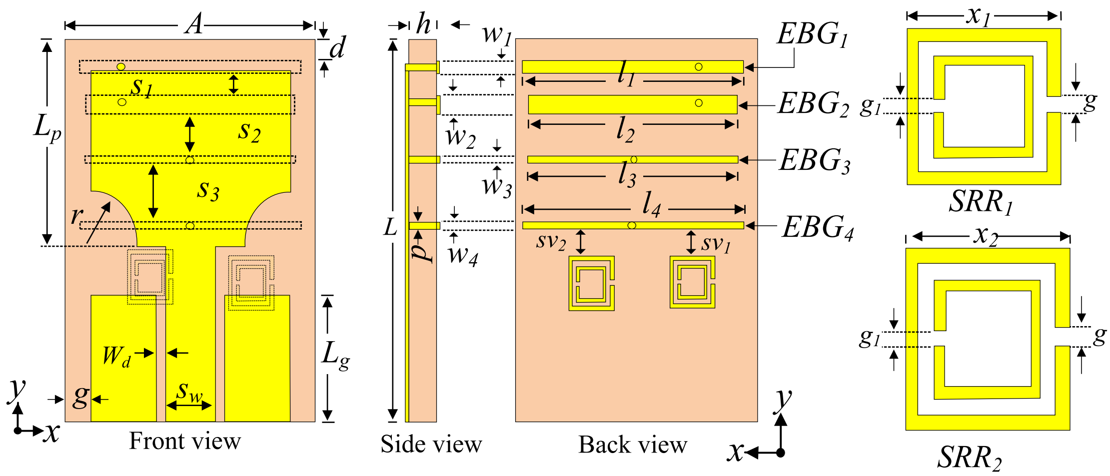

FIGURE 10. The geometry of the proposed antenna.

fr can then be achieved. The configuration schematic view and equivalent circuit model of the EBG structure are shown in figure 2 (a) and (b). Therefore, this technique is used in this work. The EBG structure absorbs the current from a specific region of the radiator of the antenna [26], [27]. Initially, an EBG structure is loaded on the backside of the substrate, which is connected to the radiating element via a shorting pin. A conventional notch is achieved by optimizing the parameters of EBG_1 such as length l_1, and width w_1, and the position of EBG structure. This typical notch does not reject the interference with high selectivity offered by unwanted bands. Therefore, we need to find a technique that rejects interference perfectly. Then, another EBG_2 is added to the antenna to realize another conventional notch at the required frequency of the 5G sub-6 GHz band. Hence by optimizing parameters of EBG_1 and EBG_2 (l_1, w_1, l_2, w_2, and s_1,) the two conventional notches are then combined to achieve a highly selective notch to reject maximum interference. The $|S_{11}|$ characteristics of antennas can be seen in Figure 3 where the conventional notch is improved to a highly selective rectangular notch for maximum interference rejection. The geometry of the conventional notch antenna and rectangular notch band antenna with EBG structures is shown in Figure 4. Furthermore, the parametric study of the EBG structure is also carried out for better understanding. It is to be noted that during the parametric study, only one parameter is changed, and all other parameters are fixed. Figure 5 shows the $|S_{11}|$ of the antenna according to different width (w_2) variations of EBG_2. The upper frequency of the notch band shifted linearly toward the left side with an increase in the w_2 without affecting the passband of the antenna and the notch has little shift towards the right side with a decrease in EBGs width. The variations in the length (l_2) of EBG_2 also have a similar effect that is shown in Figure 6. These observations indicate that by tuning the dimensions of the EBGs, we can acquire the desired rectangular notch by tuning the length, width, and position of EGB carefully.

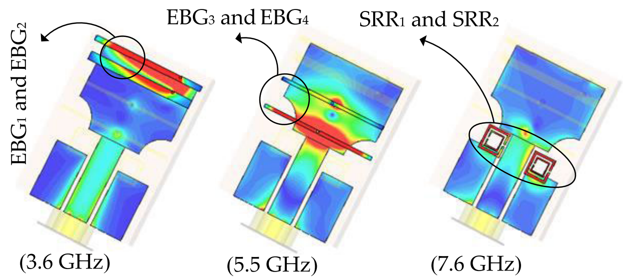

FIGURE 11. The current distribution of the antenna at different notched frequencies.

B. 5G AND WLAN-BAND (5.15 – 5.85 GHz) REJECTION

To realize a rectangular notch as aforesaid requires two EBG structures. Therefore, two more EBGs are loaded on the backside of the antenna to create a rectangular notch at WLAN-band. The antenna design is shown in Figure 7.

A high selective rectangular notch is realized after optimizing the parameters (l_3, w_3, s_2, l_4, w_4, and s_3) of EBG_3 and EBG_4. As the EBGs are creating bandgaps by absorbing electromagnetic waves, the addition of every single EBG affects the previous results which require reoptimizing parameters of all EBGs. The distance between two EBG structures, their width, and length is optimized to realize a rectangular notch with high selectivity at the WLAN band. Due to use of two more EBG structures for rectangular notch at WLAN band. It is worth mentioning that the parametric study carried out for the previous bandgap is used for the WLAN band rejection. The $|S_{11}|$ characteristics of the antenna with 5G and WLAN band are shown in Figure 8.

C. PROPOSED ANTENNA FOR TRIPLE RECTANGULAR NOTCH BANDS

The antenna radiating patch length is only 12 mm. The gap between two EBGs helps to attain the rectangular notch characteristic. Four EBG structures are added already to notch 5G

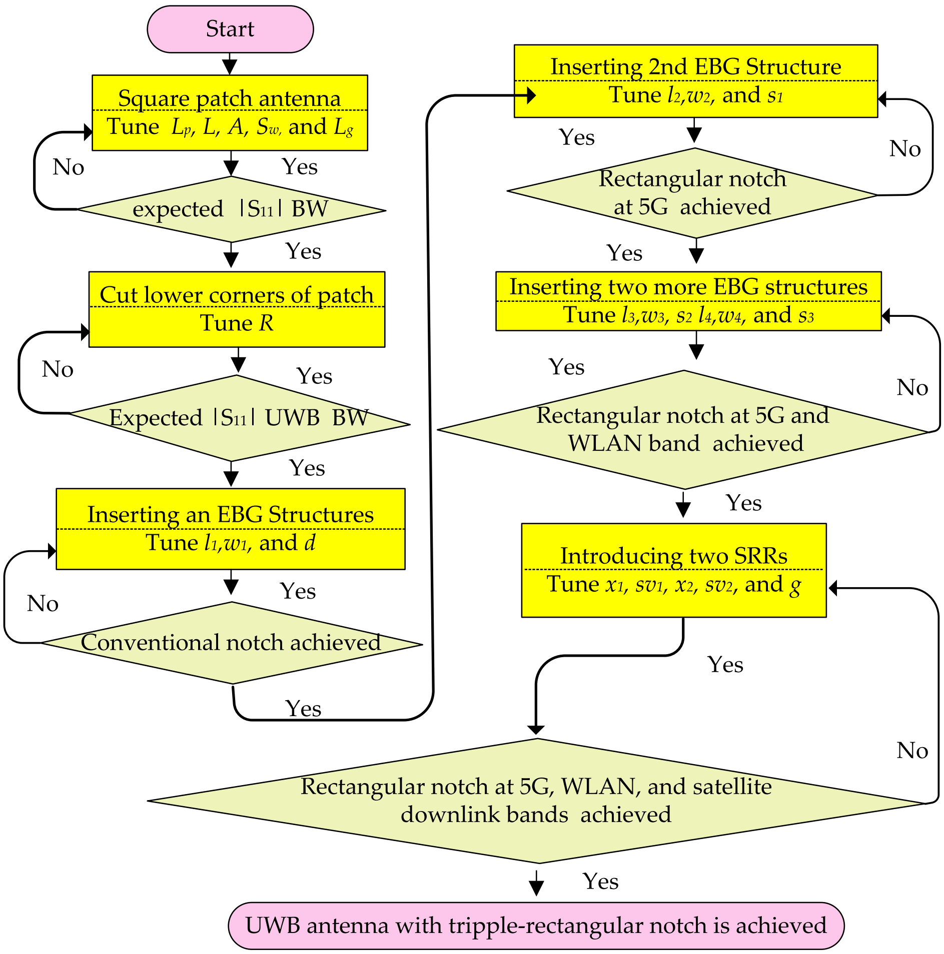

FIGURE 12. Design procedure of the proposed antenna with triple rectangular notch-band characteristics.

and WLAN band. Almost the length of the radiating patch is utilized to accommodate the EBGs. Therefore, it is realized that to avoid interference from more bands another technique must be considered.

The SRR is constructed by two coexisting split rings. The SRR induces a perpendicular magnetic field that is responsible for the negative value of permeability, because of a magnetically resonant structure. A split gap in the inner ring introduces a capacitance that can be used to control the resonant characteristics of the structure [28], [29]. Therefore, the SRR structure is used for satellite downlink band rejection.

First, a spiculate notch is realized using a single SRR_1 that is added on the backside of the antenna's feed line. Then by optimizing parameters like length x_1, the gap created g, and the location of SRR_1 (sv_1) a conventional notch is produced two conventional notches. By optimizing the parameters of SRR_1 and SRR_2, the individual notch bands are merged to form a rectangular notch at the satellite downlink band. For further demonstration, the $|S_{11}|$ characteristics of the antenna for one and two SRRs is shown in Figure 9.

The proposed antenna geometry is shown in Figure 10. The proposed antenna achieved three rectangular notch bands at 5G sub-6 GHz, WLAN, and satellite downlink bands.

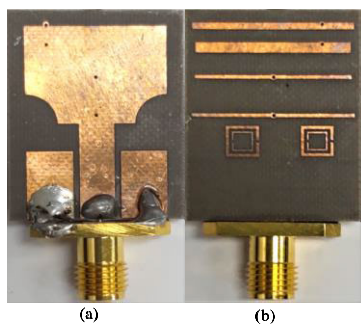

FIGURE 13. Photo of fabricated UWB antenna with a triple-rectangular notched band: (a) front side (b) backside.

The surface current distribution at different stop-bands is plotted in Figure 11, to further demonstrate the stop-band mechanism. It can be observed that at 3.6 GHz, the current is concentrated only in EBG_1 and EBG_2. While at 5.5 GHz the current flow on EBG_3 and EBG_4. At 7.6 GHz the current is maximum at both SRRs. This observation verifies that the first set of EBGs (EBG_1 and EBG_2) are creating a 5G sub-6 GHz notch band and the second set of EBGs (EBG_3 and EBG_4) are creating the notch at the WLAN band. While the SRRs are responsible for satellite downlink band rejection.

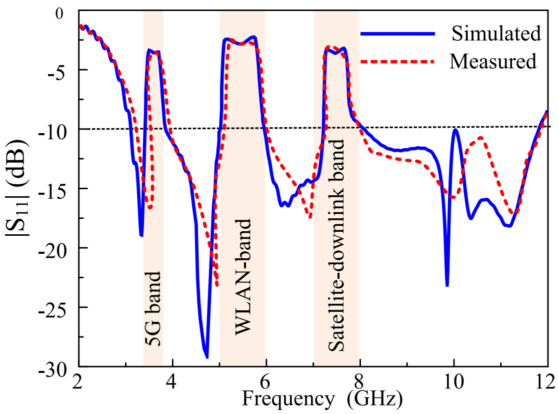

FIGURE 14. Simulated and measured $|S_{11}|$ characteristics of the proposed antenna.

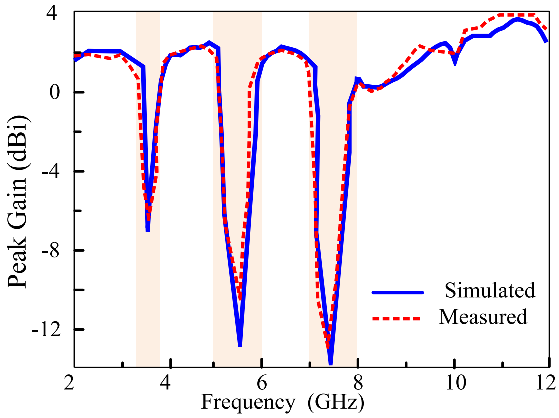

FIGURE 15. Simulated and measured gains of the proposed antenna.

The design summary of the triple-band rectangular notch UWB antenna is illustrated in the detailed flowchart shown in Figure 12. Firstly, a simple rectangular patch that is fed with a microstrip feedline with the partial ground plane is designed. The antenna parameters are then optimized for the best results. To achieve the UWB characteristics the lower end of the patch is truncated by a semicircle with R radius. Then the EBG structure is loaded and optimized its parameters (w_l, l_l, d, and p) to achieve a conventional notch. For rectangular notch, at 5G (3.4 – 3.9 GHz) one more EBG is added and its parameters (l_2, w_2, and s_1) are tuned till the best-notch band is realized. Similarly, two more EBG structures are added and optimized the parameters (l_3, w_3, s_2, l_4, w_4, and s_3) to achieve a rectangular notch at the WLAN band. For satellite downlink band rejection, two SRR are designed on the backside of the feeding line. By optimizing its parameters length (x_1, sv_1, x_2, sv_2, and g) the rectangular notch is realized.

III. ANTENNA MEASUREMENTS AND ANALYSIS

The designed UWB antenna was fabricated on Taconic TLY 5A (1.52 mm) for experimental verification shown in Figure 13. The proposed antenna's $|S_{11}|$ characteristic and the radiation patterns are measured by an Agilent Vector Network. Figure 14 depicts the $|S_{11}|$ characteristics, and

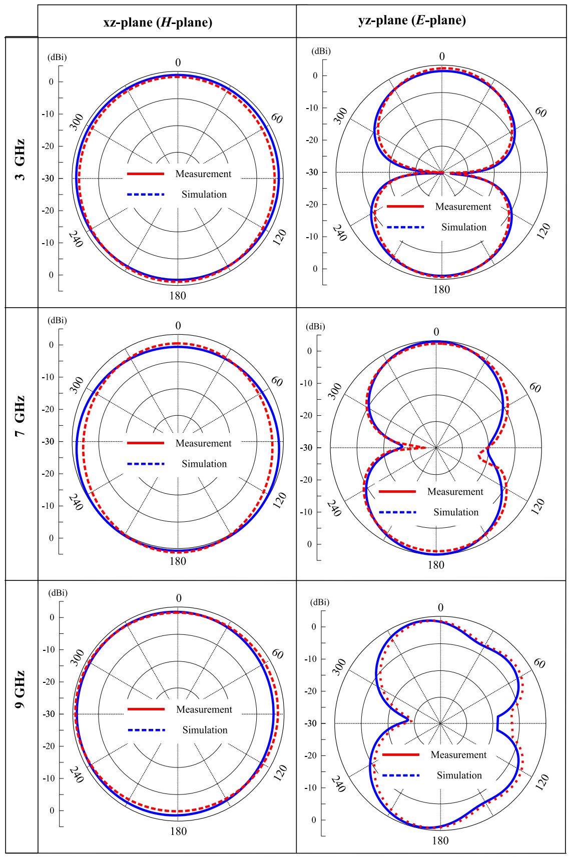

FIGURE 16. Simulated and measured radiation patterns in the E-and H-plane at 3 GHz, 7 GHz, and 9 GHz.

Figure 15 shows the measured and simulated gain results. Both results are well-matched. The peak gain curve shows the stability for frequency range with the maximum value of 3.8 dBi while there has been a sharp decrease in the rejected bands. This characteristic makes a rectangular notch antenna more effective than the conventional notch antennas.

The radiation pattern in the H-plane (xz-plane) and E-plane (yz-plane) at 3, 7, and 9 GHz of measured and simulated results are shown in Figure 16. From the overall view of these radiation patterns, the proposed antenna exhibits an Omni-directional in H-plane for both simulated and measured results. Radiation patterns at lower frequencies are stable showing bidirectional patterns while it shows little changes in higher frequencies.

Finally, a comparison with previously reported rectangular notched antennas with the designed antenna is shown in Table 1. None of the reference antennas have a triple- rectangular notching characteristics. The antennas presented [8], [10], [12], [13], [15], [17] have conventional triple notches. The antenna presented in [19], [20], [25] is offering rectangular notch-bands only the WLAN band. The design presented in [21] offers a WLAN band and satellite downlink band, using the step slot technique. References [22], [23] offer WLAN band rejection using inductively coupled-resonator pairs and etching slots on patch respectively. The antenna in [24] rejects 5G and WLAN bands,

TABLE 1. Performance comparison of the proposed antenna with the existing notched antenna.

Reference antennas	Antenna size (mm^3)	No of notch bands	Notch bands	Rectangular notch	Notching technique
[8]	19×24×1.2	3	3.3 – 3.75 GHz 5.15 – 5.82 GHz 7.25 – 7.75 GHz	No	Quarter-wavelength slots
[10]	54×47×1	3	2.23 – 2.45 GHz 3.26 – 3.48 GHz 5.54 – 5.88 GHz	No	Slots on patch and SRR on the feed line
[12]	50×42×1.6	3	3.3 – 3.8 GHz 5.15 – 5.82 GHz 7.1 – 7.9 GHz	No	EBGs
[13]	24×24×1.6	3	3.3 – 4.0 GHz 5.1 – 5.8 GHz 7.2 – 7.8 GHz	No	EBGs
[15]	40×30×0.78	4	3.39 – 3.82 GHz 5.13 – 5.40 GHz 5.71 – 5.91 GHz 7.5 – 8.61 GHz	No	SRR
[17]	30×22×3	3	3.26 – 3.71 GHz 5.15 – 5.37 GHz 5.78 – 5.95 GHz	No	Parasitic strips
[19]	48×50×1	1	5.15 – 5.82 GHz	Yes	EBGs
[20]	50 × 50 × 1.575	1	5.15 – 5.82 GHz 6.2 – 6.9 GHz	No	SRR on the feed line
[21]	28 ×18 × 0.8	2	5.1 – 6.0 GHz 7.83 – 8.47 GHz	Yes	Stepped slot
[22]	38 × 42 × 0.5	1	5.15 – 5.35 GHz	Yes	Inductively coupled resonator
[23]	8.5 × 22 × 0.8	1	5.15 – 5.82 GHz	Yes	Etched slots on patch
[24]	25 × 10 × 1	2	3.3 – 3.8 GHz 5.0 – 5.9 GHz	Yes	Coupling the parasitic strip
[25]	16×25×1.52	1	5 – 6 GHz	Yes	EBGs
This work	**20 × 26 × 1.52**	**3**	**3.4 – 3.9 GHz 5.15 – 5.82 GHz 7.25 – 7.75 GHz**	**Yes**	**EBGs and SRRs**

using the parasitic strips. In short, the proposed design has the benefit of rejecting 5G, WLAN band, and satellite downlink band with high selectivity.

IV. CONCLUSION

The proposed antenna has an impedance bandwidth of 3.1–11.8 GHz. The conventional notch is realized by using a single EBG structure, and the novel rectangular notch at the 5G and WLAN band is realized by using a pair of EBG structures. The new rectangular notch at the satellite downlink band is attained by using a pair of SRRs with optimized parameters. Simulated and measured results of triple-band notch UWB antenna have been compared which shows the rectangular notch characteristics at 5G (3.4 – 3.9 GHz), WLAN (5.15 – 5.825 GHz), and satellite downlink (7.25 – 7.75 GHz) bands as expected. The peak gain value of the UWB antenna is 3.86 dBi but it sharply decreases up to −13 dBi at stopbands.

REFERENCES

[1] R. J. Fontana, "Recent system applications of short-pulse ultra-wideband (UWB) technology," *IEEE Trans. Microw. Theory Techn.*, vol. 52, no. 9, pp. 2087–2104, Sep. 2004.

[2] Y. I. A. Al-Yasir, M. K. Alkhafaji, H. A. Alhamadani, N. O. Parchin, I. Elfergani, A. L. Saleh, J. Rodriguez, and R. A. Abd-Alhameed, "A new and compact wide-band microstrip filter-antenna design for 2.4 GHz ISM band and 4G applications," *Electronics*, vol. 9, no. 7, p. 1084, Jun. 2020.

[3] S. Nelaturi and N. V. S. N. Sarma, "A compact microstrip patch antenna based on metamaterials for Wi-Fi and WiMAX applications," *J. Electromagn. Eng. Sci.*, vol. 18, no. 3, pp. 182–187, Jul. 2018.

[4] J. Kim and Y. Sung, "Dual-band microstrip patch antenna with switchable orthogonal linear polarizations," *J. Electromagn. Eng. Sci.*, vol. 18, no. 4, pp. 215–220, Oct. 2018.

[5] W. A. Awan, A. Zaidi, N. Hussain, A. Iqbal, and A. Baghdad, ''Stub loaded, low profile UWB antenna with independently controllable notch-bands,'' *Microw. Opt. Technol. Lett.*, vol. 61, no. 11, pp. 2447–2454, Nov. 2019.

[6] H. Bong, M. Jeong, N. Hussain, S. Rhee, S. Gil, and N. Kim, ''Design of an UWB antenna with two slits for 5G/WLAN-notched bands,'' *Microw. Opt. Technol. Lett.*, vol. 61, no. 5, pp. 1295–1300, Jan. 2019.

[7] X. Zheng and T. Jiang, ''Triple notches bandstop microstrip filter based on archimedean spiral electromagnetic bandgap structure,'' *Electronics*, vol. 8, no. 9, p. 964, Aug. 2019.

[8] D. K. Naji, ''Miniature slotted semi-circular dual-band antenna for WiMAX and WLAN applications,'' *J. Electromagn. Eng. Sci.*, vol. 20, no. 2, pp. 115–124, Apr. 2020.

[9] N. Hussain, M. Jeong, J. Park, S. Rhee, P. Kim, and N. and Kim, ''A compact size 2.9-23.5 GHz microstrip patch antenna with WLAN band-rejection,'' *Microw. Opt. Technol. Lett.*, vol. 18, no. 3, pp. 1307–1313, May 2019.

[10] A. Iqbal, A. Smida, N. Mallat, M. Islam, and S. Kim, ''A compact UWB antenna with independently controllable notch bands,'' *Sensors*, vol. 19, no. 6, p. 1411, Mar. 2019.

[11] M. Yazdi and N. Komjani, ''Design of a band-notched UWB monopole antenna by means of an EBG structure,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 170–173, 2011.

[12] N. Jaglan, B. K. Kanaujia, S. D. Gupta, and S. Srivastava, ''Triple band notched UWB antenna design using electromagnetic bandgap structures,'' *Prog. Electromagn. Res. C.*, vol. 66, pp. 139–147, 2016.

[13] M. A. Trimukhe and B. G. Hogade, ''Compact Ultra-wideband antenna with triple band notch characteristics using EBG structures,'' *Prog. Electromagn. Res. C.*, vol. 8, no. 7, pp. 1069–1075, Nov. 2016.

[14] S.-W. Qu, J.-L. Li, and Q. Xue, ''A band-notched ultrawideband printed monopole antenna,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 5, pp. 495–498, 2006.

[15] M. J. Jeong, N. Hussain, H. Bong, J. W. Park, K. S. Shin, S. W. Lee, S. Y. Rhee, and N. Kim, ''Ultrawideband microstrip patch antenna with quadruple band notch characteristic using negative permittivity unit cells,'' *Microw. Opt. Technol. Lett.*, vol. 62, no. 2, pp. 816–824, Feb. 2020.

[16] J. Kim, C. S. Cho, and J. W. Lee, ''5.2 GHz notched ultra-wideband antenna using slot-type SRR,'' *Electron. Lett.*, vol. 42, no. 6, pp. 315–316, Mar. 2006.

[17] M. T. Islam, R. Azim, and A. T. Mobashsher, ''Triple band-notched planar UWB antenna using parasitic strips,'' *Prog. Electromagn. Res.*, vol. 129, pp. 161–179, 2012.

[18] F.-C. Ren, F.-S. Zhang, J. H. Bao, Y.-C. Jiao, and L. Zhou, ''Printed Bluetooth and UWB antenna with dual band-notched functions,'' *Prog. Electromagn. Res. Lett.*, vol. 26, pp. 39–48, 2011.

[19] L. Peng, B.-J. Wen, X.-F. Li, X. Jiang, and S.-M. Li, ''CPW fed UWB antenna by EBGs with wide rectangular notched-band,'' *IEEE Access*, vol. 4, pp. 9545–9552, 2016.

[20] J. Y. Siddiqui, C. Saha, and Y. M. M. Antar, ''Compact dual-SRR-loaded UWB monopole antenna with dual frequency and wideband notch characteristics,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 100–103, Sep. 2015.

[21] W.-A. Li, Z.-H. Tu, Q.-X. Chu, and X.-H. Wu, ''Differential stepped-slot UWB antenna with common-mode suppression and dual sharp-selectivity notched bands,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 1120–1123, Oct. 2016.

[22] T.-G. Ma and J.-W. Tsai, ''Band-rejected ultrawideband planar monopole antenna with high frequency selectivity and controllable bandwidth using inductively coupled resonator pairs,'' *IEEE Trans. Antennas Propag.*, vol. 58, no. 8, pp. 2747–2752, Aug. 2010.

[23] Q.-X. Chu, C.-X. Mao, and H. Zhu, ''A compact notched band UWB slot antenna with sharp selectivity and controllable bandwidth,'' *IEEE Trans. Antennas Propag.*, vol. 61, no. 8, pp. 3961–3966, Aug. 2013.

[24] X.-P. Xiong, Q. Liu, Y. Zhang, and Y.-L. Luo, ''Novel ACS-fed monopole antenna for UWB applications with sharp selectivity notched band and additional Bluetooth band characteristics,'' *J. Electromagn. Waves Appl.*, vol. 28, no. 18, pp. 2308–2317, Dec. 2014.

[25] A. Abbas, N. Hussain, M.-J. Jeong, J. Park, K. S. Shin, T. Kim, and N. Kim, ''A rectangular notch-band UWB antenna with controllable notched bandwidth and centre frequency,'' *Sensors*, vol. 20, no. 3, p. 777, Jan. 2020.

[26] N. Yang, ZN. Chen, Y. Wang, and MYW. Chia, ''A two-layer compact electromagnetic bandgap (EBG) structure and its applications in microstrip filter design,'' *Microw. Opt. Technol. Lett.*, vol. 37, no. 1, pp. 62–64, Apr. 2003.

[27] L. Peng and C.-L. Ruan, ''UWB band-notched monopole antenna design using electromagnetic-bandgap structures,'' *IEEE Trans. Microw. Theory Techn.*, vol. 59, no. 4, pp. 1074–1081, Apr. 2011.

[28] M. Islam, M. Islam, M. Samsuzzaman, M. Faruque, and N. Misran, ''A negative index metamaterial-inspired UWB antenna with an integration of complementary SRR and CLS unit cells for microwave imaging sensor applications,'' *Sensors*, vol. 15, no. 5, pp. 11601–11627, May 2015.

[29] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, ''Magnetism from conductors and enhanced nonlinear phenomena,'' *IEEE Trans. Microw. Theory Techn.*, vol. 47, no. 11, pp. 2075–2084, 1999.

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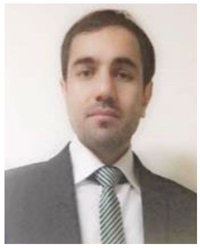

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