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Printed circular ultra-wideband antenna with triple sharp frequency notches for surface penetrating radar application

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Abstract. A printed ultra-wideband antenna of compact size (0.36 $\lambda_L \times 0.31\ \lambda_L$) that delivers bandwidth ($S_{11} \leq -10$ dB) of 2.64–9.36 GHz (112%), with triple notches at 3.28–3.84, 5.08–5.44 and 5.62–6.06 GHz to reject contemporaneous wireless interventions such as WiMAX and WLAN is reported in this article. The proposed antenna performance is established by both simulation and experimental measurement. The antenna affords gain variation from 2 to 5 dBi, radiation efficiency of 80% on an average, linear transfer function and non-varying group delay response in its pass bandwidth while significant deviations are observed in the three notch bands. Bi-directional E-plane and non-directional H-plane patterns are testified in the antenna pass band. Antenna bandwidth is also measured in proximity of soil, wood and glass by keeping metal plate at bottom where an unaltered bandwidth response is observed that justify its capability to work for surface penetrating application.

Keywords. Ultra-wideband (UWB) antenna; frequency notch; printed circular monopole; surface penetrating radar (SPR).

1. Introduction

With extensive growth in the wireless communication segment and inclusion of new technologies for high speed data transmission, accommodating different neighbor wireless standards is one of the prime norms in antenna design. Ultra-wideband (UWB) antenna found supreme potential because of its ability to handle enormous raw data with very low transmission power [1]. However dissociating multiple neighbor frequency standards in such wide spread bandwidth is really a challenging task. One possible way to achieve it is by establishing filtering ability in the antenna performance to ensure the rejection of unwanted frequency bands. Such scheme is better than integrating antenna with filter because of lower package size and less complexity in design and implementation. The frequency stop band generation in UWB is achieved in different possible ways. Entrenching of differently shaped slots like U [2], V [3], T [4] on antenna patch, feed and ground plane are considered in earlier literatures. However this strategy has one serious restriction of realizing notch band with very poor quality (Q) factor, where Q-factor is formulated as the ratio of notch center frequency to notch band. Other popular notch production processes are implanting different stub [5], strip [6] and resonating structures such as mushroom-shaped electromagnetic band gap [7], open loop resonator [8] in the antenna geometry, loading split ring resonator pair in the close proximity of feed [9]. However all such methods can provide only single frequency stop band which is insufficient considering the huge spectrum of UWB.

Recently several works are reported to produce multiple frequency notch bands in UWB. Xu *et al* proposed dual band notched UWB antenna of size 56 × 45 mm^2 that provides wide impedance band from 3 to 12 GHz with stop bands centered at 3.5 and 4.8 GHz [10]. Jeon *et al* proposed an Archimedean spiral antenna of dimension 36 × 36 mm^2 to cover impedance band of 3.1–10.5 GHz with 5.15–5.95 GHz frequency notch [11]. UWB antenna of dimension 80 × 70 mm^2 that offers bandwidth from 1.5 to 12 GHz with four notches at 2.15–2.65, 3–3.7, 5.45–5.98, and 8–8.68 GHz is proposed in [12]. A compact balloon-shaped UWB antenna of dimension 27.5 × 16.5 mm^2 to cover an impedance band from 1.75 to 10.3 GHz with dual notches at 2.2–3.9 and 5.1–6 GHz is proposed in [13]. Peddakrishna and Khan proposed an UWB monopole antenna of dimension 40 × 52 mm^2 that offers wide bandwidth from 2.7 to 11.7 GHz with dual notch bands at 3.3–3.7 and 6.5–7.2 GHz [14]. Awan *et al* proposed compact CPW fed UWB antenna of size 20 × 23 mm^2 that

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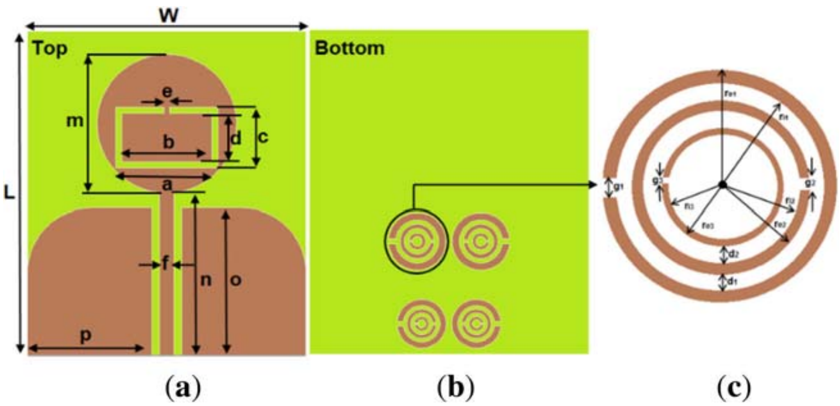


Figure 1. Schematics of the proposed antenna: (**a**) top view, (**b**) bottom view and (**c**) three- layered circular SRR.

offers bandwidth from 3.2 to 10.5 GHz with dual notches at 4–5.78 and 6.83–8.22 GHz [15]. However in all these reported works, the proposed frequency notches are having limited Q-factor that implies losses of valuable spectrum. Siddiqui *et al* also proposed multiple frequency notched UWB antipodal tapered slot antenna [16] but bulky profile restricted the usage of this antenna in various applications.

One possible application of UWB antenna is in surface penetrating radar (SPR) where improved lateral resolution is desired [17]. Li *et al* proposed a bulky slot antenna of dimension 10.6 × 6.8 cm^2 that offers bandwidth from 1.4 to 3.5 GHz with moderate gain and less dispersion [18]. Ahmed *et al* proposed an UWB antenna that is used for air coupled ground penetrating radar application [19]. Apart from air coupled applications, UWB antenna can be very useful for ground coupling SPR application [20–22]. However due to extensive wide impedance band profile, the UWB antenna can interfere with other co-existing wireless application and to avoid such possibility it is desired to have multiple notches in its working band.

2. Design of antenna and notch structures

The basic configuration and performance of modified circular monopole UWB antenna is proposed in [23] which covers an extensive impedance band from 3.1 to more than 20 GHz. Hybrid notch generation strategy is adopted in this antenna as shown in figure 1. To employ WiMAX notch band (3.3–3.7 GHz), a rectangular split ring resonator (SRR) slot is etched out from the circular radiator near to feed gap. Couples of unique three layered circular SRR pairs are entrenched at the lower end substrate and opposite to the feed. The bigger SRR pair is employed to get the lower WLAN whereas smaller SRR pair is employed to realize upper WLAN notch. The design parameters of the SRR slot can be estimated from the following equation,

$$f_n = \frac{c}{4[a+d-2e)]\sqrt{\varepsilon_{eff}}} \tag{1}$$

Here, $\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}$ and ε_r indicates relative dielectric constant of the substrate material that is 4.4. As shown in figure 1(a), the outer peripheral length and width of the SRR slot are represented by a and d. Split gap of rectangular SRR is indicated by g. c represents speed of light. By controlling the design parameters of three layered CSRR, notch center frequencies can be varied. The design parameters of CSRR pairs can be calculated from the following equation,

$$f_{notch} = \frac{c\sqrt{3d/r}}{2\pi^2 r\left(\sqrt{\varepsilon_{eff}}+g\right)} \tag{2}$$

Here, $d = \frac{d_1+d_2}{2}$ where d_1 and d_2 represent spacing between circular split rings as shown in figure 1(c). Also in equation 2, $\varepsilon_{eff} = \frac{\varepsilon_r+1}{2}$, $g = \frac{g_1+g_2+g_3}{3}$ and $r = \frac{r_1+r_2}{2}$ where, $r_1 = \frac{r_{i1}+r_{o2}}{2}$; $r_2 = \frac{r_{i2}+r_{o3}}{2}$.

The equivalent circuit model of three-layered circular SRR is drawn in figure 2. An EMF created when magnetic field is served to the CSRR along the z axis that couples two neighbor circular split rings with induced current that passes through the space capacitance which is formed between the rings. Also inductance formed due to current flow between the rings. The distributed capacitances C_1, C_2

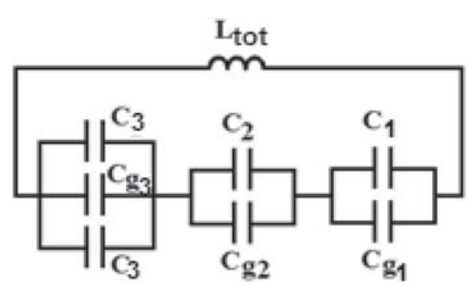
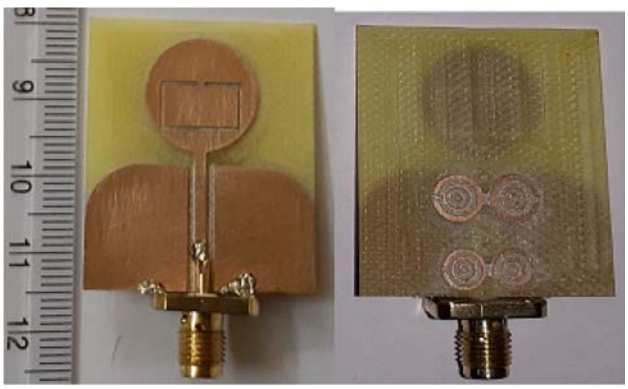


Figure 2. Equivalent circuit model of CSRR.

Table 1. Optimal dimensions of proposed notched antenna.

Param.	Value	Param.	Value	Param.	Value
L	$0.36\lambda_L$	c	$0.06\lambda_L$	m	$0.155\lambda_L$
W	$0.31\lambda_L$	d	$0.05\lambda_L$	n	$0.17\lambda_L$
a	$0.11\lambda_L$	e	$0.006\lambda_L$	o	$0.16\lambda_L$
b	$0.1\lambda_L$	f	$0.01\lambda_L$	p	$0.14\lambda_L$



(a) (b)

Figure 3. Prototype of (**a**) top and (**b**) bottom of proposed antenna.

and C_3 are formed at both the halves of CSRR and in between neighboring rings. Gap capacitances C_{g1}, C_{g2} and C_{g3} are created because of the splits in circular rings. The notch resonance f_0 due to the proposed CSRR can be calculated using,

$$f_0 = \frac{1}{2\pi\sqrt{L_{tot}C_{tot}}} \quad (3)$$

Here C_{tot} denotes total capacitance that can be calculated from,

$$C_{tot} = \frac{(2C_3 + C_{g3})(C_2 + C_{g2})(C_1 + C_{g1})}{(2C_3 + C_{g3})(C_2 + C_{g2}) + (C_2 + C_{g2})(C_1 + C_{g1}) + (2C_3 + C_{g3})(C_1 + C_{g1})} \quad (4)$$

L_{tot} denotes total inductance that can be find out from,

$$L_{tot} = \frac{r_{o1}}{100 \times 25.4}\left[7.4log\frac{32r_{o1}}{r_a} - 6.4\right]\mu H \quad (5)$$

Here, r_a can be calculated from equation (6),

$$r_a = \frac{(r_{o1} - r_{i1}) + (r_{o2} - r_{i2}) + (r_{o3} - r_{i3})}{3} \quad (6)$$

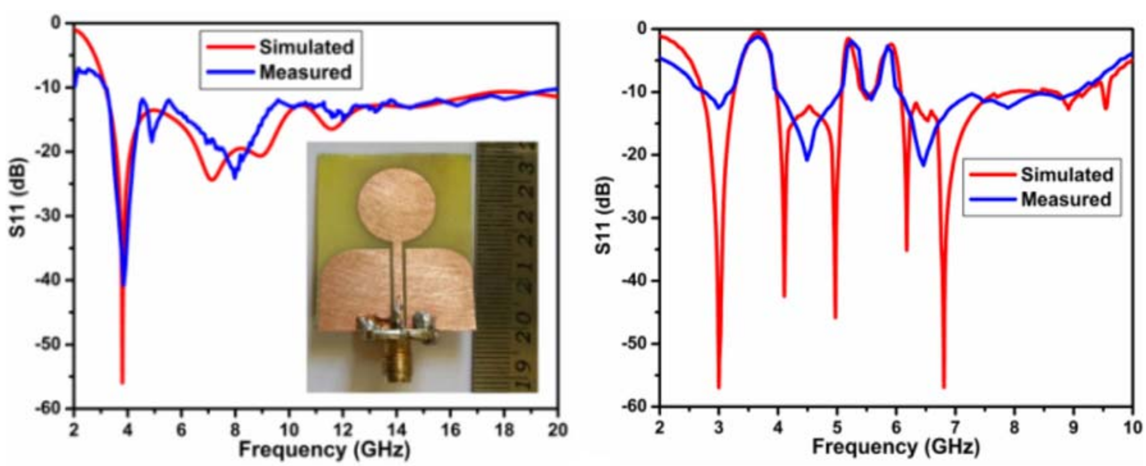
The notch center frequencies of bigger and smaller CSRR pairs are calculated as 5.14 GHz and 5.86 GHz, respectively using the equations from (3) to (6). Final values of design parameters are given in table 1.

The proposed antenna is designed and optimized in CST microwave studio suite simulator [24]. As given in figure 3, the proposed antenna is fabricated on 0.8 mm thick FR4 epoxy substrate.

3. Results and discussion

3.1 *Performance of triple notched antenna*

The proposed antenna performances are compared and established by both simulation in CST studio suite simulator and experimental measurement. The S_{11} profile of the reference antenna is plotted in figure 4(a). Clearly, the



(a) (b)

Figure 4. Simulated and measured S_{11} response of (**a**) reference antenna, (**b**) proposed triple notched antenna.

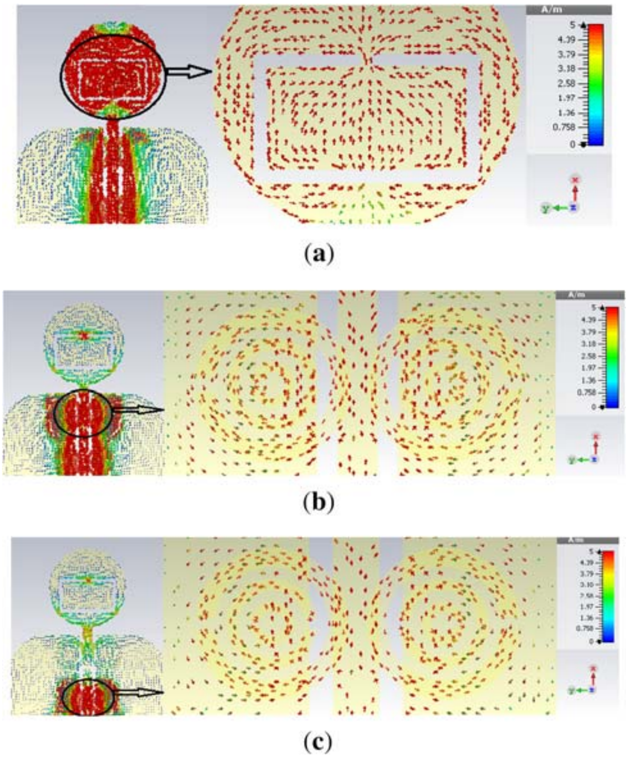


Figure 5. Simulated surface current on antenna at (**a**) 3.62, (**b**) 5.2 and (**c**) 5.92 GHz.

antenna offers a widespread impedance band from 3.1 to more than 20 GHz. The reflection coefficient over frequency is also plotted for the proposed triple notched antenna in figure 4(b). Impedance band ranging from 2.64 to 9.36 GHz with sharp triple notches at 3.28–3.84, 5.08–5.44 and 5.62–6.06 GHz are obtained from measured outcome that makes a good covenant with simulated plot.

Surface currents on the proposed antenna are simulated at three notch centre frequencies and plotted in figure 5. Clearly dense current distributions can be observed around the respective notch structures which are rectangular SRR slot at 3.62 GHz, bigger CSRR pair at 5.2 GHz and smaller CSRR pair at 5.9 GHz. The rectangular SRR shaped slot adds excess opposite directional current path inside and outside the slots which cancels each other to produce zero current and thus offers robust notch resonance. Similarly, the three-layered CSRR pairs also produce additional current flow in reverse directions in and around the metallic split rings to realize robust notch resonances.

Co-polarized radiation patterns of the proposed triple notched antenna are plotted at 4.5, 7 and 9 GHz in figure 6. Bi-directional monopole likes E-plane and non-directional H-plane patterns can be observed. A good agreement in between the simulated and measured plots can also be seen.

As plotted in figure 7(a), the proposed antenna delivers a stable gain response over its operating pass band which is varying from 2 to 5 dBi. Good correlation between the simulated and measured results is seen. However the gain responses degrade radically in the three frequency stop bands that evidence the notch creation in these frequency bands.

The proposed antenna provides radiation efficiency of almost 90% on an average in its pass band as per simulation plot, however it reduces to about 80% as per measured plot as can be seen in the figure 7(b). Substantial fall in the radiation efficiency can be seen at three frequency notch bands that validate the strong notch creation in these three bands. The radiation efficiency measurement is carried out following the modified wheeler's cap method as proposed in [25].

Antenna group delay (GD) and transfer function (S_{21}) response are decisive measure to analyze its transient performance. GD and S_{21} measurement in face to face orientation is shown in figure 8(a). Here, two similar prototypes of the proposed antennas are connected to both the ports of R&S ZVL 13 VNA. As can be seen in figure 8(b), the proposed antenna exhibits almost flat GD response and linear S_{21} response in its pass band. However, strong deeps can also be seen in the triple notch bands which actually

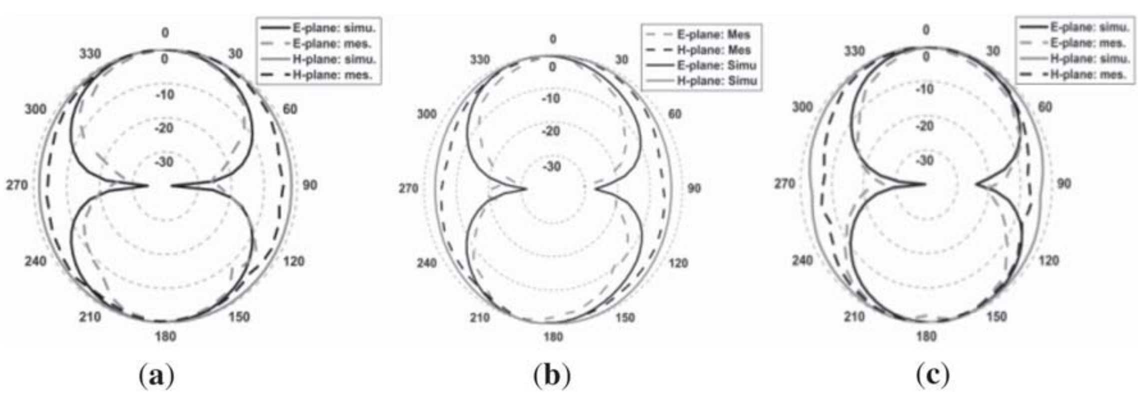
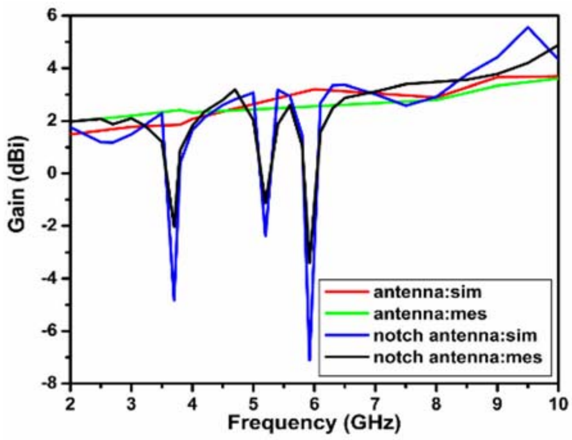
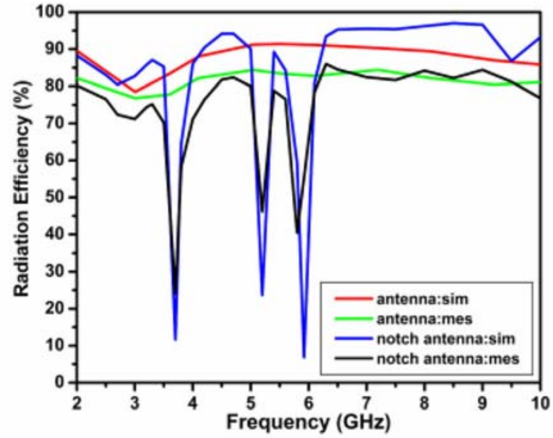


Figure 6. E-plane and H-plane antenna radiation patterns at (**a**) 4.5, (**b**) 7 and (**c**) 9 GHz.



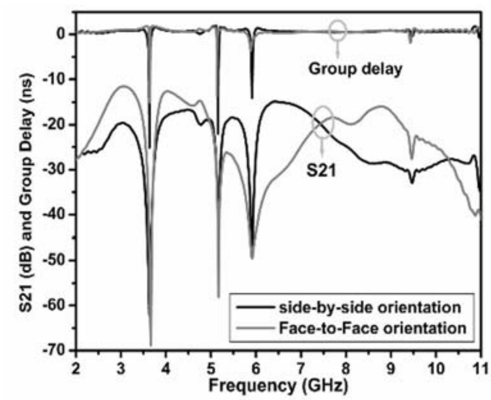
(a)



(b)

Figure 7. Simulated and measured comparison plot for reference antenna and the proposed triple notched antenna of (**a**) Gain over frequency, (**b**) radiation efficiency over frequency.

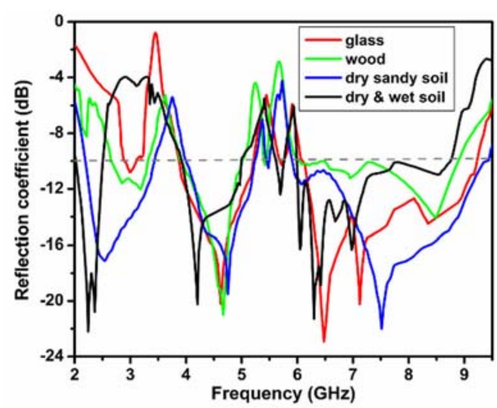
(a)



(b)

Figure 8. (**a**) Measurement set-up (face to face orientation) and (**b**) plot of magnitude response of antenna transfer function (S_{21}) and group delay (side by side and face to face orientation).

(a)



(b)

Figure 9. (**a**) S_{11} measurement set-up in proximity of soil test bed, (**b**) plot of reflection coefficient (S_{11}) in proximity of various surfaces.

Table 2. Comparison of proposed UWB notched antenna with other recently reported UWB multi notched antennas.

Ref./ Year	Notch generating method	No. of Notch	Pass band (GHz)	Notch-band (GHz)	*Gain (dBi)	*Avg. Rad. Eff.
[10]/ 2014	SLRR slot	2	3–12	Centered at 3.5 and 4.8	1.5–6.5	80%
[12]/ 2017	Systematic defection slots	4	1.5–12	2.15–2.65, 3–3.7, 5.45–5.98, 8–8.68	0–6	75%
[13]/ 2018	U-slot and Parasitic resonator	2	1.75–10.3	2.2–3.9, 5.1–6	2–4.5	80%
[14]/ 2018	π-shaped slot and EBG resonator	2	2.7–11.7	3.3–3.7, 6.5–7.2	1–5	Not given
[16]/ 2018	SRR	Variable	0.4–9	2.55; 2.95; 3.2; 4.1	5–10	Not given
[15]/ 2019	Circular split ring slots	2	3.2–10.5	4–5.78 and 6.83–8.22	0.5–4.83	95%
This work	SRR slot and CSRR	3	2.64–9.36	3.28–3.84, 5.08–5.44, 5.62–6.06	2–5	80%

*All given values are valid for antenna pass band only.

justify the creation of strong frequency notch in these frequency bands.

3.2 *Antenna performance in proximity of various surfaces*

The proposed multi notched antenna can be very useful for high lateral resolution surface scanning because of its wide bandwidth with multiple desired sharp notch bands. The antenna bandwidth is measured in close proximity of two inch thick glass, wood, dry sandy soil and a mixture of dry and wet sandy soil where an aluminium sheet is buried at the bottom. The measurement scheme for dry soil test bed is shown in figure 9(a). The antenna bandwidth remains almost unaltered in proximity of all different surfaces as can be seen in figure 9(b). The similar pass band and stop band response for all of the varying surfaces establish the fitness of the proposed multi notched UWB antenna in SPR.

4. Conclusion

A simple design of compact printed UWB antenna with prominent triple notch bands to abolish the probabilities of intrusion from contemporaneous wireless bands such as IEEE 802.16 WiMAX (3.3–3.7 GHz), IEEE 802.11y (3.65–3.69 GHz), IEEE 802.11 WLAN (5.15–5.35 and 5.725–5.825 GHz), IEEE 802.11p DSRC (5.85–5.925 GHz), and Industrial, scientific and medical (ISM) band (5.725–5.875 GHz) is proposed. The major attainment in this work is to produce the frequency stop bands with very high Q-factor and thus eluding the loss of valuable spectrum. The proposed antenna also offers high radiation efficiency with stable gain response, linear transfer function profile and smooth group delay response as experienced by simulation and experimental measurement. All these quality mark the proposed antenna suitable for high speed short range UWB communication applications including SPR. The performance of the proposed antenna is compared with some of the newly reported notched antennas in table2. The proposed antenna is having best notch performance as it offers properly tuned multiple notches in desired bands with very sharp roll-off factor.

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