Design & parametric analysis of band reject ultra wideband (UWB) antenna using step impedance resonator

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Tejbir Singh1,2*, Heena Choudhary3, D.V. Avasthi3 and Vishant Gahlaut4

Abstract: The design and analysis of step impedance resonator (SIR) based, compact and band-notch UWB antenna, to minimize the potential interference between wide-band (UWB) and narrow-band (WLAN), has been presented in this paper. The notched band covers the 5.15 GHz to 5.85 GHz WLAN range. The frequency band has been obtained by embedding a SIR near the radiating patch of the antenna. The empirical relationship between the SIR design and band-notch characteristics has also been included in the paper. The UWB patch antenna structure is feed by micro-strip line. The parametric-analysis by varying the parameters the SIR as well as the substrate has been performed, to observe the optimal performance the proposed antenna. The design and functional simulation of the proposed antenna structure is performed by using HFSS-v14. A close agreement between simulated and experimental results for the proposed design has been observed and presented in this paper. The design and results provide ample justification for compatibility and application of the structure in UWB communication over the entire frequency range.

Subjects: Electrical & Electronic Engineering; Electromagnetics & Communication; Telecommunication

Keywords: step impedance resonator (SIR); ultra wide-band (UWB); wireless local area network (WLAN); patch antenna

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PUBLIC INTEREST STATEMENT

Wireless connectivity has enabled a new mobile lifestyle filled with conveniences for mobile computing users. Consumers will soon demand the same conveniences throughout their digital home, connecting their PCs, personal digital recorders, digital cameras, high-definition TVs, personal digital assistants, and cell phones, to connect to each other in a wireless personal area network (WPAN) in the home. But today’s wireless LAN and WPAN technologies cannot meet the needs of tomorrow’s connectivity of such a host of emerging consumer electronic devices that require high bandwidth. Ultra-wideband (UWB) technology offers a solution for the bandwidth, high data rates across multiple devices, cost, power consumption, and physical size requirements of next-generation consumer electronic devices for digital home and the office. In this context, the UWB antenna design plays a unique role because it behaves like a band pass filter and reshapes the spectra of the pulses and avoid undesired distortions.
1. Introduction
The Ultra wideband (UWB) is a wireless communication technology, which provide a short-range communication from 4 meters to 10 meters, with a low output power and high data rate (up to 1 Gbps) in 3.1–10.6 GHz the frequency range (Federal Communications Commission, 2002). Some other narrowband applications such as, IEEE802.11a (5–6 GHz) and WiMAX (3.3–3.6 GHz) also exists along with the UWB range (Agrawall, Kumar, & Ray, 1998; Chu & Yang, 2008). Therefore, the design of an UWB antenna with band-notch characteristics is a prime requirement to diminish the potential interference between UWB and co-existing narrowband services.

The micro-strip antennas are popular in a wide variety of applications due to their low profile, simple design, conformability to planar and non-planar surfaces, low cost and ease in manufacture with modern printed circuit technology. The radiating patch can be square, rectangular, bow-tie, circular or any other shape. However, the bow-tie configuration is generally preferred in UWB applications because of its ability for bandwidth enhancement and miniaturization (Bahadori & Samii, 2007; Schantz, Wolenec, & Myszka, 2003; Yao, Huang, & Feng, 2007). Recent researches have shown significant interest in the design and analysis of UWB antenna systems in the wireless communication (Da Xu et al., 2015; Kadam, Gudino, Ramesha, & Nagaraju, 2016; Min, Zhang, Zhong, & Chen, 2016).

The main challenge in UWB antenna design is to achieve impedance matching and bandwidth control in simultaneity along with high radiation efficiency and low EMI effects (Daniels, 1996; Kerkhoff & Ling, 2007; Shaman & Hong, 2007). The planar antenna feature is also desirable given that there are several additional constraints and challenges for the design of a UWB antenna system (Choi, Kim, Hwang, & Choi, 2014; Chung, Hong, & Choi, 2007; Ma & Wu, 2007; Ojaroudi, Ojaroudi, & Ghadimi, 2013; Ojaroudi, Yazdanifard, Ojaroudi, & Sadeghzadeh, 2011; Yang, Jin, Vittoria, Harris, & Sun, 2008; Zhang et al., 2008). The design and validation of SIR based compact bow-tie antenna with band rejection characteristics is the prime objective of this paper. In this design, the ground plane structure has been taken uneven. The concluding part of the Paper presents a parametric analysis by including various design parameters such as SIR and a ground plane.

2. Antenna design
The parametric analysis of the proposed compact band-rejection antenna structure is based on transmission line modal analysis (Chen, Chia, & Ammann, 2003). The detailed geometry and parameters of the proposed antenna structure are depicted in Figure 1 and Table 1 respectively. The simulation results for the proposed antenna structure are obtained with uneven ground patch followed by the parametric analysis of various design parameters of the system.
The proposed design has the dimension of $18 \times 27.5$ mm$^2$ fabricated on the Taconic RF60 substrate with a thickness of 0.64 mm and relative dielectric constant of 6.15, which is having loss tangent ($\tan \delta$) 0.0023. The width $W_2$ of the micro-strip feed line is fixed at 1 mm.

Figure 1 depicts the detailed structure of the compact band-rejection antenna, on the upper surface of the substrate, a half bow-tie shape radiating patch shown in Figure 2(a) and the uneven ground plane shown in Figure 2(b) respectively.

By embedding a resonator, it is observed that rejection of WLAN band can be accomplished for the proposed structure, thus it is beneficial to minimizing the EMI problem between UWB and WLAN. The resonator referred in this model is a step impedance resonator. From the electrical viewpoint, it is a non uniform transmission line, i.e. a transmission line with the cross section varying in steps and each step is having a different electrical length and impedances. As per the wave cancellation theory, when two signals with identical properties and a phase shift of 180º interact with each other at a particular frequency, the resultant signal becomes zero at that particular frequency.

The structure of SIR referred to in this paper is a series combination of different impedances as depicted in Figure 3(b) and (c). The SIRs generate second harmonics depending upon the difference of SIR impedances, which is responsible for creating the band rejection. The second harmonics and the length of transmission line are determined by the following equations (Lee, Kim, Kim, & Yu, 2006):

$$f_{s2} = (xf)/(2 \tan^{-1} \sqrt{K})$$  
(1)

$$K = Z_1/Z_2$$  
(2)

$$\theta_{SIR} = \tan^{-1} \sqrt{K}$$  
(3)

Equations (1)–(3) show that the frequency of the second harmonics, which is two times of the base frequency in the unitary impedance resonator. Therefore, it can be predicted that the second harmonics would be generated at frequencies given by the following conditions:

| Parameter | Data | Parameter | Data |
|-----------|------|-----------|------|
| Frequency | 6.2 GHz | $W_1$ | 18 mm |
| Length of substrate $L$ | 27.5 mm | $W_{g1}$ | 2.5 mm |
| Width of substrate $W$ | 18 mm | $W_{g2}$ | 3 mm |
| Height of substrate $h$ | 0.64 mm | $W_{g3}$ | 7 mm |
| Length of patch $L_1$ | 27.5 mm | $W_{g4}$ | 11 mm |
| Width of patch $W_1$ | 16 mm | $L_{g1}$ | 3 mm |
| $W_2$ | 1 mm | $L_{g2}$ | 2.75 mm |
| Substrate material | Taconic RF-60A | $d_1$ | 2.8125 mm |
| $d_2$ | 1.62 mm | $L_{g3}$ | 5.75 mm |
| $\theta_{sir}$ | 9.844 mm |
The conditions given in Equation (4) shows the second harmonic frequency can be adjusted in accordance with the variables in the equation. The initial length of the SIR ($\theta_{SIR}$) is predetermined by the center frequency of the stop band. The most important design parameters to be decided are the gap, $d_1$ and $d_2$ of SIR as depicted in the geometry of Figure 4.

\[
\begin{align*}
    f_{\text{hi}} &< 2 f_0 \quad \text{when } K < 1 \\
    f_{\text{hi}} &> 2 f_0 \quad \text{when } K > 1
\end{align*}
\] (4)
3. Simulation results

Figure 5 shows the simulated return losses (S parameter) of the antenna having multi-band characteristic in the UWB spectrum.

![Figure 3. Types of impedance resonator: (a) Unitary impedance resonator. (b) and (c) Types of step impedance.](image)

It is observed from Figure 5 that the UWB antenna covers 2.8–10.8 GHz range with a return loss less than −10 dB except the rejection band 5.15–5.9 GHz. The result indicates that the proposed antenna structure is having return loss less than −10 dB, which is fairly low over the entire UWB range.

The VSWR of the proposed antenna structure with optimized parameters is shown below in Figure 6. It is observed from the Figure 6 that the simulated VSWR characteristic of the proposed antenna possesses one exact band notch or frequency rejection band with 5.15–5.9 GHz for WLAN.

4. Parametric analysis

4.1. Effect of variation of the position of SIR

The plot depicted below in Figure 7 shows the comparison of characteristics corresponding to different RL curves pertaining to variation in the position of the resonator (SIR) in X-axis.
The variation in the position of SIR in X-axis causes a change in the bandwidth of the stop-bands shown in Table 2. There exists a relation between the two i.e. the position of SIR and the bandwidth of the stop band. Nearer positioning of SIR to radiated patch results in larger bandwidth of the stop-band, while further positioning results in smaller bandwidth of stop-band.
4.2. Effect of variation of initial length of SIR

The plot depicted below in Figure 8 shows a comparison of the characteristics to different RL curves corresponding to variation in the initial length of the resonator.

Table 3 shows that the variation in the initial length of SIR causes a change in the center frequency of the stop-band. There exists a relation between the two i.e. the initial length of SIR and the Centre Frequency of the rejection band. A greater length of the SIR results in smaller central frequency of the stop-band and vice versa.

4.3. Effect of variation of d₁, d₂ of SIR on the covered bandwidth

It is observed from Figure 9 that a RL curve corresponding to different widths d₁ and d₂ of the step impedance resonator and proves the relation between the two d₁, d₂ and bandwidth. It is observed that an increase in d₁ and d₂ decreases the bandwidth of the proposed antenna and vice versa, which is indicated in Table 4.
4.4. Effect of variation of substrate material

The curve depicted below in Figure 10 shows the effect of the variation of substrate material of the proposed UWB Antenna structure without any tuning in antenna dimensions.

FR4-epoxy has a lowest value of $\varepsilon_r$ in the substrate materials included in Table 5, which is implying larger bandwidth than other two dielectric materials at the cost of Q-factor. At the same time the dielectric Taconic RF60-A has a moderate value of covered bandwidth, which is sufficient for UWB application with low loss tangent $\delta$ implying low energy losses in the material. Similarly Rogers RT/duroid6010 have high Q-factor, but less bandwidth, which cannot fulfill the requirement of UWB application. These attributes justify Taconic RF60-A dielectric as appropriate for fabrication of the proposed antenna structure.

4.5. Effect of variation of substrate thickness

The graph depicted below in Figure 11 shows the effect of the variation of substrate thickness of the proposed UWB antenna structure on its covered bandwidth resonant frequency performance.

The thickness of the substrate is increased progressively from $h = 0.44$ to 0.74 mm in three steps. It is observed that:
(a) The increase in substrate thickness $h$ then increases the fringing fields at the edges, which in turn increases the effective length $L$ of the patch, thereby reducing the resonant frequency of the system. This apart, the increase in $h$ reduces $W/h$ ratio, thus reducing effective relative permittivity $\varepsilon_{\text{eff}}$ of the dielectric causing increase in resonant frequency of the system. One important observation is made as, the performance of the antennas increase as $\varepsilon_r$ decrease. Therefore, the net effect of the variation in substrate thickness is the overall decrease the...
resonance frequency due to the dominance of the effect of varying $L_{\text{eff}}$. Hence, when the thickness ($h$) is increased from 0.44 to 0.74 mm, the resonant frequency decreases from 4.69 to 4.54 GHz.

(b) As $h$ is increased from 0.44 to 0.74 mm, the impedance bandwidth increases from 5,620 to 8,150 MHz. Therefore, by increasing the substrate thickness, the bandwidth can be enhanced. But, the substrate thickness cannot be increased beyond an extent as that would make surface waves dominant. This necessitates judicious selection of substrate thickness for realizing higher bandwidth.

This justifies the selection of substrate thickness, $h = 0.64$ mm in the instant case as it results in a large bandwidth.
4.6. Effect of variation of width $W_g$ of ground

The curve depicted below in Figure 12 shows the effect of the variation of width of ground plane relating to the proposed UWB Antenna structure.

It is observed that the antenna bandwidth increases as the ground width $W_g$ is increased and vice versa shown in Table 7 and Figure 12 above. At a specific value of ground plane width, there is an impedance matching and a minimum return loss is achieved (see Figure 13).
The measured and simulated S11 of the proposed antenna with single band notched characteristics shown Figure 14. The measurement of S11 was carried out with a network analyzer Agilent N5230 (10 MHz to 20 GHz). A relatively good agreement between measurement and simulation has been observed. It is found that the input impedance of the fabricated antenna is well matched as the bandwidth covers the entire UWB band (3.1–10.6 GHz).

The axial ratios are often quoted for antennas in which the desired polarization is circular. The ideal value of the axial ratio for circularly polarized fields is 0 dB. In addition, the axial ratio tends to degrade away from the mainbeam of an antenna, so the axial ratio may be indicated in a data sheet for an antenna as follows:

**Axial Ratio < 3 dB for ± 30 degrees from main beam.**

This indicates that the deviation from circular polarization is less than 3 dB over the specified angular range (see Figure 15).

The axial ratio can be calculated from:

\[
AR = \frac{|E_{RHCP}| + |E_{LHCP}|}{|E_{RHCP}| - |E_{LHCP}|}
\]  

And the cross polarization is:

\[
XPD = \frac{|E_{RHCP}|}{|E_{LHCP}|}
\]
Figure 15. Comparative graph for simulated $E_{RHCP}$ and $E_{LHCP}$ of the proposed UWB antenna structure (a) at 4 GHz and (b) at 8 GHz.

Table 6. Effect of substrate thickness on bandwidth

| Substrate thickness ($h$) | Resonant frequency ($f_r$) | BW               |
|--------------------------|---------------------------|------------------|
| $h = 0.44$ mm            | $f_r = 4.69$ GHz          | 5,620 MHz (3.75–9.37 GHz) |
| $h = 0.64$ mm            | $f_r = 4.62$ GHz          | 7,990 MHz (2.83–10.82 GHz) |
| $h = 0.74$ mm            | $f_r = 4.54$ GHz          | 8,150 MHz (2.58–10.73 GHz) |
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5. Conclusion
This work, as evidenced from the characteristic curves and Tables 2–7 included in the paper has been successfully designed and realized the proposed microstrip antenna structure with a half bow-tie patch and miniaturization, which makes it suitable for UWB applications. The proposed antenna has impedance bandwidth covering the entire UWB range (2.8–10.8 GHz), along with rejection-band in the WLAN (5.15–5.85 GHz). A prototype antenna is fabricated by using low-cost Taconic RF60 substrate. Overall, the performance of the proposed antenna meets the desired requirements in terms of return loss (<−10 dB) and VSWR (<2).

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Table 7. Simulation result with the variation of ground plane width Wg of the proposed structure

| Ground plane width (Wg) | Covered bandwidth     |
|-------------------------|-----------------------|
| Wg = 16.5 mm            | 3.05–8.89 GHz (5,840 MHz) |
| Wg = 17.0505 mm         | 2.91–10.6 GHz (7,690 MHz) |
| Wg = 18 mm              | 2.8–10.8 GHz (8,000 MHz) |

\[ XPD = 20\log \left( \frac{AR + 1}{AR - 1} \right) \text{ dB} \] (7)

where; XPD is cross polarization.
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