A compact coplanar waveguide (CPW)-fed ultra-wideband (UWB) antenna is proposed with band-notched characteristic. The antenna has compact size of 29 x 31 mm. A novel wide polygon-slot is inserted on the antenna to obtain good impedance matching and wide bandwidth. A tapered radiating patch is placed inside the polygon-slot. An embedded C-slot in the radiating patch avoids potential interference from WLAN band. The antenna is fabricated and measured. The measured results confirm that the antenna has operating frequency band of 3.1-10.6 GHz with notched band of 5.1-5.9 GHz. The antenna has stable radiation patterns and consistent gain over operating band. The time domain group delay of antenna is within 1 ns except in notched band, which indicates good linear phase response. The results indicate that the antenna is good for portable UWB systems.

Index Terms— band rejection, group delay, impedance matching, slot, UWB.

I. INTRODUCTION

Since Federal Communication Commission (FCC) released a frequency band of 3.1-10.6 GHz for commercial UWB applications, UWB technology has gained attention in both industry and academia. UWB systems have various merits such as lower power consumption and high data transmission rate. UWB antenna is one of the key elements in UWB systems. Hence, design of UWB antenna has gained attraction in wireless field. Since small antennas are required for portable systems, miniaturization of UWB antenna has become important research topic. Planar slot antennas [1]-[3] have become popular among recently proposed antennas due to small size, wide bandwidth and ease of integration with RF front ends.

Several narrow band communication systems such as IEEE 802.11a wireless local area network (WLAN) bands (5.15-5.35 GHz and 5.725-5.825 GHz) in USA and high performance radio local area network/2 (HIPERLAN/2) bands (5.15-5.35 GHz and 5.470-5.725 GHz) in Europe, exist in ultra-wide bandwidth. Hence, potential interference from these bands should be avoided for good performance of UWB antenna. UWB filters [4], [5] have been designed to suppress the undesired bands. However, use of filter increases complexity of overall UWB system. Hence, it is required to design UWB antenna with band-notched characteristics. Various UWB antennas with band-notched techniques...
have been proposed in literature such as cutting a $\pi$-slot [6], [7], arc-slot [8] in patch, embedding a tuning stub in slot [9], [10], inserting a slit in patch [11] and placing parasitic elements near feed [12], [13]. However, the time domain analysis of UWB antenna is not analyzed with mathematical expressions. The CPW feed is popular because it has wider bandwidth, lesser dispersion and lower radiation loss than microstrip line.

In this paper, a compact UWB slot antenna is presented with band-rejection characteristic. By inserting a C-slot in the radiating patch, the interfering signals from WLAN band are avoided. The geometry of antenna is presented in section II with band-notched design. The parametric study of antenna is analyzed in section III. The measured radiation patterns and gain are discussed in section IV. The time domain analysis of antenna is analyzed in section V. The time domain group delay of antenna is with in 1ns except in notched band. The transient response of antenna is explained with mathematical expressions. Section VI concludes the paper.

II. ANTENNA GEOMETRY AND BAND-NOTCHED DESIGN

The antenna is fabricated on FR4 substrate with dielectric permittivity $\varepsilon_r = 4.4$, loss tangent $\tan\delta = 0.02$ and thickness $h = 0.8$ mm. The antenna has compact size of $29 \times 31$ mm$^2$. The antenna is fed by 50 $\Omega$ CPW line. The CPW feed is terminated with subminiature version A (SMA) connector. A single metallic layer and small size make the antenna to integrate with RF front ends easily. A novel polygon-slot was chosen to obtain wide bandwidth and good impedance matching over the bandwidth. Hence the parameters $W_3$, $L_3$ and $L_4$ are optimized to obtain good impedance matching over UWB. A radiating tapered patch is placed inside polygon-slot as shown in Fig. 1.

![Fig. 1. Geometry of the proposed UWB antenna.](image-url)

A ‘C’ shaped slot is inserted in the radiating patch of antenna to avoid interference from WLAN and HIPERLAN/2 bands as shown in Fig. 1. Since the slot is considered as half wave resonator, guided wavelength is used to obtain total length of C-slot. When the length of the C-slot is about half...
of guided wavelength $\lambda_g$, the slot resonates at notch frequency $f_0$ and behaves as short circuit in parallel to input impedance of the antenna. Hence, the antenna does not work in the frequencies around $f_0$ and it avoids the potential interference from WLAN band from 5.1GHz to 5.9GHz. Let, the total length of C-slot [14] is denoted by $L_{\text{slot}}$ and it is obtained by

$$L_{\text{slot}} = \frac{\lambda_g}{2} = \frac{c}{2 f_0 \sqrt{\varepsilon + 1/2}}$$  

(1)

where $\lambda_g$ is guided wavelength corresponding to notch frequency $f_0$, $c$ is velocity of light in free-space and $\varepsilon_r$ is dielectric permittivity of FR4 substrate. Initially, C-slot is designed theoretically to resonate at notch frequency $f_0 = 5.5$ GHz to obtain total length of C-slot according to equation 1. In practice, the notch frequency $f_0 = 5.5$ GHz is obtained when the total length of C-slot is $L_{\text{slot}} = W_{f1} + 2W_{f2} + 2L_{f1} + 2L_{f2}$ as shown in Fig. 1 in the design of antenna structure with IE3D electromagnetic solver. Hence, the length $L_{\text{slot}}$ is practically equal to $0.6\lambda_g$ where $\lambda_g = \lambda_0 / \sqrt{\varepsilon_{\text{eff}}}$ and $\varepsilon_{\text{eff}} = (\varepsilon_r + 1)/2$. Here, $\lambda_0$ is wavelength corresponding to the notch frequency $f_0 = 5.5$ GHz, $\varepsilon_{\text{eff}}$ is effective dielectric permittivity of dielectric substrate and $\varepsilon_r$ is dielectric permittivity of the substrate.

The proposed fabricated antenna with the total length of C-slot $L_{\text{slot}}$ confirms the measured notched frequency 5.5 GHz as shown in Fig. 2.

![Fig. 2. Simulated and measured return losses of proposed antenna.](image)

![Fig. 3. Photograph of the fabricated antenna.](image)

The antenna parameters are optimized based of method of moments based IE3d electromagnetic optimizer. The optimized parameters of the proposed antenna are $W = 29$ mm, $W_1 = 12.65$ mm, $W_2 = 2.8$ mm, $W_3 = 5$ mm, $W_4 = 1$ mm, $W_5 = 1.75$ mm, $W_6 = 5$ mm, $W_7 = 4$ mm, $W_8 = 10.5$ mm, $W_{f1} = 5.5$ mm, $W_{f2} = 2.75$ mm, $L = 31$ mm, $L_1 = 8$ mm, $L_2 = 2.2$ mm, $L_3 = 4$ mm, $L_4 = 4.5$ mm, $L_5 = 10.25$ mm, $L_6 = 2$ mm, $L_7 = 1.1$ mm, $L_{f1} = 4.2$ mm, $L_{f2} = 0.5$ mm, $g = 0.45$ mm. The fabricated antenna is measured with Agilent E8362B network analyzer. The simulated and measured return loss curves of proposed antenna are shown in Fig. 2. Good agreement is found between measured and simulated...
return loss curves. The difference between them is mainly due to effect of soldering at SMA connector and slight variation of dielectric permittivity, dissipation factor at high frequencies. The antenna has impedance bandwidth of 3.1-10.6 GHz with a notched band from 5.1 GHz to 5.9 GHz. The Fig. 2 shows that the measured UWB antenna has three resonating frequencies 3.8 GHz, 6.2 GHz and 8.8 GHz. The photograph of fabricated antenna is shown in Fig. 3.

III. PARAMETRIC ANALYSIS

The effect of few sensitive parameters on the performance of antenna has been studied. The analysis is done by changing one parameter, keeping all other parameters constant. IE3d simulator is used in this analysis.

A. Effect of intrusion depth $L_2$

The intrusion depth $L_2$ affects impedance matching and bandwidth of antenna as shown in Fig. 4. It causes more current distribution at bottom part of patch and top edge of ground plane as shown in Fig. 9(a) when $L_2$ is 2.2 mm. This parameter produces impedance mismatching when $L_2$ changes from 2.2 mm. Hence, $L_2$ is optimized to obtain better coupling from feed line to patch. The simulation results show that the antenna has poor impedance matching at $L_2 = 1.2$ mm. As $L_2$ increases, the second resonant frequency changes slightly. The first and third resonant frequencies shift left and impedance bandwidth also varies. The antenna covers entire ultra-wide bandwidth at optimum value $L_2 = 2.2$ mm. Table I shows the effect of intrusion depth on simulated lower cut-off frequency $f_{lower}$, upper cut-off frequency $f_{upper}$ and resonating frequencies. It is clear that $f_{upper}$ decreases and $f_{lower}$ remains constant with increase in $L_2$. Hence, the impedance bandwidth decreases. The simulated resonant frequencies also change.

B. Effect of length $L_{f1}$ of C-slot

If slot height $L_{f1}$ increases from 3.7 mm to 4.7 mm, the total length of C-slot increases. The notch frequency $f_0$ of WLAN changes from 5.9 GHz to 5.4 GHz as shown in Fig. 5. This is mainly due to
the fact that the length of slot $L_{slot}$ is inversely proportional to notch frequency $f_0$ of slot as mentioned in equation 1. When $L_{slot}$ is 4.2 mm, the C-slot resonates at the notch frequency 5.5 GHz and WLAN band is avoided due to abrupt change in impedance. As $L_{slot}$ varies from 4.2 mm, WLAN and HIPERLAN/2 bands are not fully avoided as shown in Fig. 5. Hence, the notch frequency in WLAN band is controlled by the slot height $L_{l1}$. Table II shows the effect of length $L_{l1}$ on simulated lower cut-off frequency $f_{lower}$, upper cut-off frequency $f_{upper}$, notch frequency $f_0$ and notch bandwidth. As $L_{l1}$ increases, notch frequency decreases and $f_{lower}$, $f_{upper}$ remain constant. The frequency range of notched-band changes.

Table I. Effect of $L_{2}$ on simulated lower cut-off frequency $f_{lower}$, upper cut-off frequency $f_{upper}$, and simulated resonant frequencies

<table>
<thead>
<tr>
<th>$L_{2}$ (mm)</th>
<th>$f_{lower}$ (GHz)</th>
<th>$f_{upper}$ (GHz)</th>
<th>Simulated resonating frequencies (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>2.88</td>
<td>11.04</td>
<td>3.8, 6.14, 10.25</td>
</tr>
<tr>
<td>2.2</td>
<td>2.88</td>
<td>10.61</td>
<td>3.4, 6.10, 9.39</td>
</tr>
<tr>
<td>3.2</td>
<td>2.88</td>
<td>9.99</td>
<td>3.29, 5.98, 8.40</td>
</tr>
</tbody>
</table>

Table II. Effect of $L_{l1}$ on simulated lower cut-off frequency $f_{lower}$, upper-cut-off frequency $f_{upper}$ and simulated notch frequency $f_0$ and simulated notch bandwidth

<table>
<thead>
<tr>
<th>$L_{l1}$ (mm)</th>
<th>$f_{lower}$ (GHz)</th>
<th>$f_{upper}$ (GHz)</th>
<th>Notch frequency, $f_0$ (GHz)</th>
<th>Simulated Notch Bandwidth (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>2.88</td>
<td>10.61</td>
<td>5.9</td>
<td>5.57-6.22</td>
</tr>
<tr>
<td>4.2</td>
<td>2.88</td>
<td>10.61</td>
<td>5.5</td>
<td>5.12-5.88</td>
</tr>
<tr>
<td>4.7</td>
<td>2.88</td>
<td>10.61</td>
<td>5.4</td>
<td>4.78-5.62</td>
</tr>
</tbody>
</table>

Fig. 6. Simulated return loss curves of antenna for different heights $L_{3}$.

C. Effect of height $L_{3}$ at upper part of ground plane

The influence of height $L_{3}$ on resonant frequencies and bandwidth of antenna is observed. As $L_{3}$ decreases from 7 mm to 1 mm, the value of second resonant frequency decreases as shown in Fig. 6.
The impedance matching at second resonant frequency deteriorates. The impedance matching is better at optimized value of \( L_3 = 4 \text{ mm} \). Hence, this parameter plays important role in improving impedance match around second resonant frequency.

![Radiation Patterns](image)

Fig. 7. Measured radiation patterns of proposed antenna in E-plane at (a) 3.8 GHz (b) 6.2 GHz (c) 8.8 GHz.

![Radiation Patterns](image)

Fig. 8. Measured radiation patterns of proposed antenna in H-plane at (a) 3.8 GHz (b) 6.2 GHz (c) 8.8 GHz.

IV. RADIATION PATTERN AND CURRENT DISTRIBUTION

The radiation patterns are measured using anechoic chamber. Figs. 7, 8 present co-polarization, cross polarization radiation patterns of the band-notched antenna in both E and H planes at measured resonant frequencies 3.8 GHz, 6.2 GHz, 8.8 GHz. The antenna has figure of eight shaped radiation patterns in E-plane which indicate that the antenna has bidirectional radiation patterns in this plane. The antenna has stable omni directional radiation patterns in H plane except at 8.8 GHz. The radiation pattern is slightly deviated from omni directional pattern in H-plane at 8.8 GHz. This is mainly due to presence of higher order modes at higher frequencies.

The radiation pattern relates to current distribution over entire operating band. Fig. 9 represents the simulated current distribution at resonant frequencies 3.8 GHz, 5.5 GHz, 6.2 GHz and 8.8 GHz. At 3.8 GHz, the surface current distribution is mainly on feed line, lower portion of patch, outer edge of patch and edges of the ground plane as shown in Fig. 9(a). Hence, these regions contribute more to radiation. At notch frequency of 5.5 GHz, strong surface current distribution concentrates at the edges.
of C-slot and flows back to feeding cable as shown in Fig. 9(b). Hence, the high impedance at the slot changes to nearly zero impedance at feed cable. Hence, there is abrupt change in impedance matching and this impedance mismatch rejects WLAN band. At 6.2 GHz, the X-directed current distribution produces cross polarization in H-plane.

![Surface current distribution on antenna at (a) 3.8 GHz (b) 5.5 GHz (c) 6.2 GHz (d) 8.8 GHz.](image)

Fig. 9. Surface current distribution on antenna at (a) 3.8 GHz (b) 5.5 GHz (c) 6.2 GHz (d) 8.8 GHz.

At 8.8 GHz, the cross polarization increases as shown in Fig. 8(c) because of presence of more X-directed current components at lower part of patch and top edge of ground plane as observed in Fig. 9(d). Fig. 10 represents measured gain of antenna against frequency. The antenna has consistent gain that changes from 2.1 dBi to 5.8 dBi in UWB except in notched band. There is sharp decrease of gain around 5.5 GHz in notched band. This confirms rejection of WLAN and HIPERLAN/2 bands.

**V. TIME DOMAIN ANALYSIS**

Since group delay presents phase linearity in far-field, it is an important parameter in time domain. Hence, group delay measurement is obtained by keeping two identical antennas at a distance of 20 cm at far-field in face to face orientation. Fig. 11 shows the time domain group delay response. The graph indicates that the group delay variation is within 1 nano second except in notched band. Hence, the
antenna has linear phase response and good pulse handling capability.

Since UWB antenna transmits pulse signals, the time domain characteristic of UWB antenna is important. The UWB signal propagation is important for communications. To obtain the performance of pulse transmission, two identical antennas are placed in face to face orientation, with a distance of 20 cm between them. The scattering transmission parameter $S_{21}$ of antenna is measured and the transfer function $H(\omega)$ [15] of antenna is obtained from $S_{21}$ as

$$H(\omega) = j \frac{\omega R}{c} e^{-j\omega R / c}$$

(2)

where $c$ is velocity of light in free-space, $R$ is distance between two identical antennas and $\omega$ is angular frequency. The input pulse is Gaussian modulated cosine pulse with amplitude factor $A = 1$, pulse width $T = 200$ picoseconds and centre frequency $f_c = 6.5$ GHz. The time domain input waveform $i(t)$ is represented by

$$i(t) = A \cos(2\pi f_c t) e^{-t^2/(T^2)}$$

(3)
The input waveform represented by equation 3 is shifted in time domain by 2.5 ns to avoid negative time and is shown in Fig. 13. The normalized power spectral density (PSD) for indoor emission mask is coded in matlab for input waveform mentioned in equation 3 with a time shift of 2.5 ns and is presented in Fig. 12. The spectrum of input pulse satisfies UWB indoor emission mask specified by FCC from 3.1 GHz to 10.6 GHz as shown in Fig. 12. The output waveform \( o(t) \) is computed by the inverse Fourier Transform of product of \( H(\omega) \) and spectrum of input signal \( I(\omega) \) and is given by

\[
o(t) = F^{-1}(H(\omega).I(\omega)) \tag{4}
\]

The time domain input and output pulses are displayed in Fig. 13. The slight ringing effect in received pulse is mainly due to transmission characteristics of the system. The received waveform indicates proper transient response for the proposed antenna. Hence, the antenna has good time domain response and it can be used for UWB communications.

VI. CONCLUSION

A compact printed planar UWB slot antenna is presented with band-notched characteristic. The desired notched band of 5.1-5.9 GHz is obtained by inserting C-slot in radiating patch to avoid interference from WLAN and HIPERLAN/2 bands. The antenna operates from 3.1 GHz to 10.6 GHz, except over notched band of 5.1-5.9 GHz. The radiation patterns are stable over UWB. The gain of antenna is almost flat except in the notched band. The group delay of antenna indicates linear phase response and good pulse handling capability. The antenna can be easily integrated with microwave integrated circuits. The antenna is good for portable UWB systems.

ACKNOWLEDGMENT

The authors would like to express sincere gratitude to the scientist, U. S. Pandey, for providing measurement facilities in LRDE lab at Defence Research Development Organisation (DRDO), Bangalore, Govt. of India.

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