Chapter 5

Investigations on planar coplanar waveguide (CPW) fed UWB monopole antennas and band-notched characteristics

5.1 Introduction

This chapter discusses the various results of the investigations carried out to find the antenna characteristics in a finite ground coplanar waveguide (CPW) fed monopole antennas with single, dual, triple and quad band-notched characteristics. For ease of fabrication and better integration, a CPW feed is employed and it also offers several advantages including low dispersion, better impedance matching, minimized radiation loss, easy surface mounting of passive and active devices and the finite ground plane between two adjacent lines make CPW ideally suitable for MIC and MMIC applications. The surface current distributions on the antenna and their radiation patterns at the typical resonant modes are analyzed in detail. From the detailed experimental and simulation studies, a detailed parametric study which depicts the effect of various antenna parameters is carried out. To reduce the interference with the conventional WiMAX (3.3-3.7 GHz), C-band (3.7-4.2 GHz), IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz), X–band satellite communication system (7.25-7.7.5 GHz), ITU band (8.01-8.5 GHz) narrow operating bands a notch band is also introduced by the different wavelength sized slots, strips and parasitic patches are
embedded on radiating patches. The analysis includes simulation studies using Ansoft HFSS and measured results with Vector Network Analyzer (VNA). Time domain analysis of the designed antennas is also studied which is suitability of pulse based applications.

5.2 Design of CPW-fed disk UWB monopole antenna (CDUMA)

This section describes the design and development of new CPW fed disk UWB monopole antenna (CDUMA). The CPW feeding mechanism has more advantages over 50Ω microstripline feed, such as better impedance matching, low dispersion, less radiation loss, easy surface mounting of passive and active devices. The proper alignment can be preserve if a CPW feed is used instead of 50Ω microstripline feed because the antenna which is fed by a 50Ω microstripline may result in symmetrical error because it is required to etching on both sides of the dielectric material. Hence in this section, the 50Ω microstripline feed monopole antennas which are discussed in chapter 4 is modified to a CPW fed disk monopole to required application of modern communication systems without compromising the UWB characteristics.

5.2.1 Geometry of CDUMA

The Figure 5.1 shows the top and side view of the CDUMA. The CDUMA is consists of a disk radiation patch of radius $R = 7.9$ mm is fed by a simple 50Ω CPW feed on the substrate and a partial ground planes are composed at the top side of the substrate dimensions $W_g \times L_g$ are 11.1 mm× 14 mm.

The CDUMA consists of a circular radiating patch and it is printed on the low-cost FR-4 epoxy substrate material with relative permittivity ($\varepsilon_r$) of 4.4, thickness (h) of 1.6 mm and a tangential loss (tan $\delta$) of 0.02. The antenna is occupies on the substrate material with an area of $L \times W = 32 \times 26$ mm. The antenna has a 50Ω CPW feed of width $W_f = 3.07$ mm and length $L_f = 15.15$ mm is used. On the top side of the substrate a pair of partial conducting ground planes and gap (g) = 0.36 mm is maintained between CPW feed and the ground planes and that provides a mechanism better impedance matching with -10 dB return loss over the UWB range. At the tip of microstripline feed a microwave
source is assigned to the SMA connector. The optimal dimensions of the CDUMA are shown in Table 5.1. The photograph of CDUMA is as shown in Figure 5.2.

<table>
<thead>
<tr>
<th>Antenna Parameter</th>
<th>W</th>
<th>L</th>
<th>W_g</th>
<th>L_g</th>
<th>R</th>
<th>W_f</th>
<th>L_f</th>
<th>d</th>
<th>g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (mm)</td>
<td>32</td>
<td>26</td>
<td>11.1</td>
<td>14</td>
<td>7.9</td>
<td>3.07</td>
<td>15.15</td>
<td>0.64</td>
<td>0.36</td>
</tr>
</tbody>
</table>

**Table 5.1: The optimal parameters and their dimensions of CDUMA**

![Top and side view geometry of the CDUMA](image1)

**Figure 5.1: Top and side view geometry of the CDUMA**

![Photograph of CDUMA](image2)

**Figure 5.2: Photograph of CDUMA**
5.2.2 VSWR Characteristics

Figure 5.3 shows a measured and simulated frequency versus VSWR plots of the CDUMA. From this figure, it is clear that the measured and simulated result lies well below 2 of VSWR from 3.1 GHz. The impedance bandwidth of the proposed antenna is covering from 3.1 GHz to more than 14 GHz for VSWR ≤ 2 covering the entire UWB spectrum.

![Figure 5.3: Measured and simulation frequency versus VSWR plots of CDUMA](image)

5.2.3 Simulated current distribution and radiation patterns of the CDUMA

For the better understanding of the radiation mechanism of the CDUMA, the simulated surface current dispersions are observed at 3.5, 5.90 and 8 GHz which are shown in Figure 5.4. It can be also be observed from this figure that, the surface current densities at 3.5 GHz is mainly accumulated at the length of monopole strip corresponding to the first resonance. From the Figure 5.4 (b) and (c) it is observed that, the current density is uniformly distributing towards the edge of the radiating patch and that gives the second resonance which is dependent on the radius of the disk radiating patch, but in 5.4 (c) at the 8 GHz the weak surface current distribution observed due to combined effect of monopole strip and the ground planes and this produces degradation in its radiation pattern.
At the first and second resonance frequencies nearly omni-directional radiation patterns are obtained but at third resonances the corresponding pattern which are measured at 8 GHz is distorted its nature of omnidirectional pattern due to the combined effect of monopole and ground planes.

Figure 5.4: Simulated current distributions and 3D radiation patterns of CDUMA observed at (a) 3.5 GHz, (b) 5.90 GHz and (c) 8 GHz
5.2.4 Parametric analysis of the CDUMA

The parametric study of the CDUMA is conducted and antenna effect for the various parameters over the antenna characteristics is studied. The results and discussion on various parametric studies are discussed in this session.

5.2.4.1 Effect of ground plane length $L_g$

The effect of ground plane lengths $L_g$ is studied and illustrated in Fig 5.5. By increasing the ground plane lengths $L_g$ from 13 mm to 14.3 mm the slight shift in lower cut-off frequency towards the lower region is observed. It is also observed that, the impedance bandwidth is significantly increasing with frequency resonances at 5 GHz, 6.63 and 8.8 GHz. The optimal value of $L_g$ is found be at $14\,\text{mm}$ for better impedance matching where we get desired VSWR $\leq 2$.

5.2.4.2 Effect of ground plane length $W_g$

The effect of ground plane width $W_g$ over the VSWR characteristics is shown in Figure 5.6. In this study the ground plane width $W_g$ is varied from 9.096 mm to 11.096 mm by keeping other dimensional parameters constant. From this figure it is evident that, the lower resonant frequency has moved to lower side
Chapter 5

over the increasing the ground plane. It is important to note that the antenna provides a wide impedance bandwidth when $W_g = 11.096$ mm.

![Image](image.png)

*Figure 5.6: Variation of VSWR versus frequency plot for the different ground plane widths $W_g$ of CDUMA*

### 5.2.4.3 Effect of disk radiating patch radius

Figure 5.7 shows a simulated VSWR curves for different radius values of the disc radiating patch with their respective optimal designs. It is observed from this figure that, the lower resonance frequency decreases with increasing the value of ‘$R$’ from 6.8 mm to 7.9 mm. The lower side frequency of VSWR < 2 impedance bandwidth of the antenna is directly related to the radius of the disc radiating patch. The optimum value of ‘$R$’ is chosen as 7.9 mm.

### 5.2.5 Measured radiation patterns of CDUMA

The normalized radiation patterns of the CDUMA in E-plane and H-plane measured at 3.5, 5.9, 8 and 10 GHz are plotted in Figure 5.8 (a-d) respectively.

From these figures it is noticed that, the measured H-plane pattern is omni-directional at lower frequencies of 3.5, 5.9 GHz which is shown in Figure 5.8 (a) and (b), and is nearly omnidirectional at higher frequencies of 8 and 10 GHz but the proposed CDUMA reveals a bidirectional radiation pattern in the E-plane at all measured frequencies.

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5.2.6 Group delay of CDUMA

To examine the CDUMA performance in time domain characteristics group delay between a pair of identical antennas by keeping 300 mm distance between each other in face to face orientation also measured and discussed. Figure 5.9 shows the simulated group delay of the CDUMA. The variation of the group delay is within 2 ns with is acceptable range is observed across the UWB frequency band.

5.3 Design of WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA with inverted closed U-slot

5.3.1 Antenna Geometry

Figure 5.10 illustrates the geometry of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA. The geometry of the antenna comprised of truncated disk radiating patch with a 50Ω CPW-fed which is fabricated on a commercial low cost FR-4 dielectric substrate material having a thickness of 1.6 mm with a relative permittivity of 4.4 and $\tan \delta$ of 0.02 is employed. In this design, the
Figure 5.8: Measured radiation patterns in E- and H-plane of the proposed CDUMA measured at (a) 3.5 GHz, (b) 5.9 GHz, (c) 8 GHz and (d) 10 GHz
antenna physical structure has dimensions of $26 \times 32 \times 1.6 \text{ mm}^2$. The CPW-fed is designed with a standard equations for an impedance matching of $50 \Omega$ and dimensions of feedline width $W_f = 3.07 \text{ mm}$ and length $L_f = 15.15 \text{ mm}$ and finite ground plane dimensions are selected as $W_g = 11.1 \text{ mm}$ and $L_g = 14.5 \text{ mm}$. The gap $'g'$ between the microstripline feed and the partially truncated ground plane is $0.36 \text{ mm}$ which is selected for $50 \Omega$ impedance matching for desired impedance bandwidth with VSWR $\leq 2$. The main structure of the antenna is truncated disk radiator of truncated area of $t_1 = 9.24 \text{ mm}$ and within the total radius of $r = 10.7 \text{ mm}$ which is shown Figure 5.1 and further to obtain a band-notched characteristics at 3.3-4.2 GHz frequency band an optimized dimensions of inverted closed U-shaped slot is engraved at the center of the radiating patch.

To understand the effect of band-notched characteristics of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA, an inverted closed U-shaped slot is embedded on the truncated disk radiating patch to achieve the band-notched characteristics for 3.3-4.2 GHz which covers the WiMAX frequency spectrum. It is important to note that, the band-notched characteristics are mainly obtained by placing the slot and suitable width and length of the inverted closed U-shaped slot. The length $US_l$ and width $US_w$ of the inverted closed U-shaped slot is about half wavelength of the notch frequency band of 3.3-4.2 GHz is approximately calculated at center frequency of 3.7 GHz which covers the WiMAX frequency.
band. The mathematical formula for the calculating guided wavelength in the medium is given by,

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \text{ mm}$$  \hspace{1cm} (5.1)

where,

$$\lambda_0 = \frac{c}{f} \text{ mm}$$

and

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2}$$  \hspace{1cm} (5.2)

The $\lambda_g$ and $\lambda_0$ are the guide and free space wavelengths respectively in mm. The $\varepsilon_{eff}$, $c$, and $f$ are the effective relative permittivity, velocity of light in free space and mid frequency of the band-notch respectively. Through the parametric study the optimal design parameters of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA are given in Table-5.2. The photograph of the fabricated WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA with SMA (Sub miniature version A) at the tip of the microstripline feed is as shown in Figure 5.11.

*Figure 5.10: Geometry of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA*
Table 5.2: The optimal design parameters of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA (Unit: mm)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate width</td>
<td>26</td>
</tr>
<tr>
<td>Substrate length</td>
<td>32</td>
</tr>
<tr>
<td>Feed line width ($W_f$)</td>
<td>3.07</td>
</tr>
<tr>
<td>Feed line length ($L_f$)</td>
<td>15.15</td>
</tr>
<tr>
<td>Substrate thickness (h)</td>
<td>1.6</td>
</tr>
<tr>
<td>Length of the ground plane ($L_g$)</td>
<td>14</td>
</tr>
<tr>
<td>Width of the ground plane ($W_g$)</td>
<td>11.1</td>
</tr>
<tr>
<td>Gap between the radiating patch and ground plane (g)</td>
<td>0.5</td>
</tr>
<tr>
<td>Inverted closed U-slot width ($US_w$)</td>
<td>0.6</td>
</tr>
<tr>
<td>Inverted closed U-slot length ($US_l$)</td>
<td>27.2</td>
</tr>
<tr>
<td>Height of truncated area t1</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Figure 5.11: Photograph of the fabricated WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA

5.3.2 Measured and simulated VSWR characteristics

The proposed WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA antenna is measured by Rohde & Schwarz ZVK model 1127.8651 German make Vector Network Analyzer (VNA). Measured and simulated VSWR characteristics of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA is as shown in Figure 5.12. There is a good agreement is seen between measured and simulated one. The antenna shows the ultra-wideband performance. The band-notched characteristics are observed at 3.3-4.2 GHz due to influence of inserting inverted closed U-slot. A 2:1 VSWR impedance bandwidth from 3.1 GHz to more than 14
GHz is obtained with band-notched characteristics at 3.3-4.2 GHz which covers the WiMAX frequency band.

![Figure 5.12: Measured and simulated VSWR plots of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA](image)

### 5.3.3 Current distributions and 3D radiation patterns of WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA with inverted closed U-slot

Simulated surface current distribution and radiation patterns of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA are measured at 3.2, 3.7 and 6.2 GHz and are plotted in Figure 5.13. From this figures, it can be found that the current distributing mainly along the microstripline feed and radiating patch at 3.2 GHz and 6.2 GHz which are shown in Figure 5.13 (a) and (c) while the current distribution at the band-notched frequency, which is shown in Figure 5.13 (b) reveals that the antenna operates as an open circuit at the band-notched frequency and the current flow is mainly accumulated along the edges of the inverted closed U-slot at 3.7 GHz. So the net impedance at the center of inverted closed U-slot is singular and acts as an open circuit, which may lead to high
impedance and prevent the antenna from radiating normally due to most of the energy is reflected back. Hence, at the band-notched frequency of 3.3-4.2 the surface current distribution on the radiating patch is virtually null. The 3D radiation patterns of the proposed band-notched antenna which is measured at 3.2, 3.7 and 96.2 GHz as shown in Figure 5.13. This confirms from the Figure 5.13 (a) and (c) that the radiation patterns at 3.2 and 6.2 GHz frequencies are same which are not altered by the band-notched frequency, but at the band-notched frequency of 3.7 GHz the radiation pattern of the antenna is very much reduced. This shows that at this frequency range of 3.3-4.2 GHz the antenna is not radiating or receiving EM energy.

\[ \text{Figure 5.13: Simulated current distributions and 3D radiation patterns of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA at (a) 3.2 GHz, (b) 3.7 GHz and (c) 6.2 GHz} \]
5.3.4 Parametric analysis of WiMAX (3.3-4.2 GHz) band-notched truncated DCUMA with inverted closed U-slot

Parameter analysis of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA is made for further studies. In order to investigate the effect of band-notched characteristics by varying the inverted closed U-slot dimensions. The following subsection provides discussions on the effect of each parametric analysis.

5.3.4.1 Effect of width (US$_w$) and length (US$_l$) of inverted closed U-shaped slot:

The simulated VSWR versus frequency plot for different widths of the inverted closed U-shaped slot US$_w$ is as shown in Figure 5.14. From this figure, we can observe that, by increasing the W$_s$ values from 0.25 mm to 1.2 mm, the notched center frequency are also increased with other optimized parameters were kept constant. Figure 5.15 illustrates the simulated VSWR versus frequency of the proposed antenna for different lengths of US$_l$. As shown in this figure, the antenna achieves an impedance bandwidth of 2:1 VSWR ranging from 3.1 GHz to more than 14 GHz with band-notched characteristics at WiMAX (3.3-4.2GHz). From the Figure 5.15 it is also clear that, by increasing the lengths US$_l$ from 1 mm to 3.5 mm of inverted closed U-slot, the notch-band is shifted towards the lower frequencies. In order to confine the frequency band UWB (3.1-10.6 GHz) and for band-notched characteristics of WiMAX (3.3-4.2 GHz) the optimized design parameters of the inverted closed U-shaped slot such as US$_w$ = 0.6 mm and US$_l$ = 27.39 mm are the best choice.

5.3.5 Measured radiation patterns of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA with inverted closed U-slot

Figure 5.16 shows the typical measured radiation patterns of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA for the optimal design measured at 3.2, 3.7, 5.5 and 7.5 GHz respectively. From these figures the proposed antenna exhibits the omni-directional radiation characteristics in H-plane and bidirectional radiation patterns in E-plane at their respective frequencies. It is also
found that at the higher frequencies the radiation patterns are not attenuated as in this design of antenna.
Figure 5.16: Measured normalized radiation patterns in E-plane and H-plane of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA measured at (a) 3.2, (b) 3.7, (c) 5.5 and (d) 7.5 GHz
5.3.6 Gain of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA with inverted closed U-slot

Simulated peak gain with and without notch of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA is plotted in Figure 5.17. It is noticed from the Figure 5.17 that, the antenna gain over operating frequency bands is about 2 to 4.2 dB is observed for entire band, with sharper decrease at rejected band of WiMAX (3.2-4.2 GHz). The maximum gain 4.2 dB is observed at 10 GHz and minimum gain of -6.4 dB is observed at notch band. Hence, the designed antenna has good band-notched characteristics of WiMAX system and minimizes the potential interferences between UWB systems.

![Simulated peak gain of proposed WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA](image)

Figure 5.17: Simulated peak gain of proposed WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA

5.3.7 Group delay of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA

Since, every UWB system uses short pulse transmission; in this regard an important issue is pulse distortion by the antenna. Hence, the group delay for the face to face orientation of two identical antennas is as shown in Figure 5.18. The variation of the group delay of the antenna is 2 ns is observed over UWB
but at the vicinity of band-notched frequency region the group delay variation is highly exceeds 4ns. This group delay characteristics represents that the proposed band-notched antenna exhibits phase linearity over UWB spectrum.

![Group delay variation of the WiMAX (3.3-4.2 GHz) band-notched truncated CDUMA](image)

**Figure 5.18:** Group delay variation of the WiMAX (3.2-4.2 GHz) band-notched truncated CDUMA

### 5.4 Design of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA with inverted polygon slot

#### 5.4.1 Antenna Geometry

The geometrical configuration of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA is as shown in Figure 5.19. The antenna is fabricated on top side of the FR-4 glass epoxy substrate with a thickness \( h \) of 1.6 mm, relative dielectric constant of 4.4, and loss tangent of 0.02. The antenna consists of a disk radiation patch connected to a 50\( \Omega \) CPW-fed with a length of \( L_f \) and a width of \( W_f \) on the front side and a pair of partial ground planes on the same top side only. To improve the impedance matching of the antenna over the UWB range, a small portion of radiating patch is truncated all
Table 5.3: The optimum dimensions of the 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA (Unit: mm)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate width</td>
<td>26</td>
</tr>
<tr>
<td>Substrate length</td>
<td>32</td>
</tr>
<tr>
<td>Feed line width ((W_f))</td>
<td>3.07</td>
</tr>
<tr>
<td>Feed line length ((L_f))</td>
<td>15.15</td>
</tr>
<tr>
<td>Substrate thickness ((h))</td>
<td>1.6</td>
</tr>
<tr>
<td>Length of the ground plane ((L_g))</td>
<td>14</td>
</tr>
<tr>
<td>Width of the ground plane ((W_g))</td>
<td>11.1</td>
</tr>
<tr>
<td>Gap between the radiating patch and ground plane ((g))</td>
<td>0.36</td>
</tr>
<tr>
<td>Inverted polygon type slot width ((P_w))</td>
<td>0.87</td>
</tr>
<tr>
<td>Inverted polygon type slot length ((P_l))</td>
<td>18.5</td>
</tr>
<tr>
<td>Height of truncated area (t_1) and (t_2)</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Three sides which is shown in Figure 5.19. To create of IEEE 802.11a WLAN or HIPERLAN/2 (5.15-5.91 GHz) band-notched for the antenna, a polygon type slot is placed at the center of the radiating patch. The antenna design model and dimensions have been optimized to achieve wide impedance bandwidth (2:1 VSWR) by using ANSYS HFSS simulation software. The optimized dimensions of the 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA are listed in Table 5.3. The photograph of fabricated antenna is shown in Figure 5.20.

5.4.2 Measured and simulated VSWR characteristics

The comparison of experimental and simulated VSWR of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA is shown in Figure 5.21. From this figure it is clear that, the VSWR curves shows that the antenna covers the frequency ranging from 3 GHz to more than 14 GHz for VSWR ≤ 2 except for band-notched characteristics from 5.15-5.91 GHz. This notched band is avoided by inserting polygon-type slot at the center of the conductive patch to reduce interference from IEEE 802.11a WLAN or HIPERLAN/2. By controlling the length and width, and location of polygon-type slot, desired notched band can be obtained in order to avoid unwanted IEEE 802.11a WLAN or HIPERLAN/2.
Figure 5.19: Geometry of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA

Figure 5.20: Photograph of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA
5.4.3 Current distributions and 3D radiation patterns of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA inverted polygon slot

To understand the radiation effect and mechanism of the band-notched characteristics of the antenna the surface currents and 3D radiation patterns of the antenna is studied. The simulated current distributions at 3.79, 5.5 and 9.45 GHz for the 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA are illustrated in Figure 5.22. It can be seen that, the current densities at 5.5 GHz mainly distributed along the edges of the inverted polygon type slot which is shown in Figure 5.22 (b). The characteristics of the current distributions at 5.5 GHz which leads to near field radiation prevention, which indicates that the high energy reflection taking place and the band-notched characteristics achieved. Further, the simulated 3D radiation patterns measured at 3.79, 5.5 and 9.45 GHz. it is found that, the antenna provides almost omnidirectional radiation inclusion at resonant frequencies. It is also noticed that, by embedding the polygon type slot to the radiating patch the radiation fields are
doesn’t disturbed excluding at notched band of 5.15-5.91 GHz frequency range and slightly disturbed at higher frequency at 9.54 GHz.

Figure 5.22: Current distributions and radiation patterns of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA
5.4.4 Parametric analysis of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA inverted polygon slot

A parametric analysis and performance of the antenna has been analyzed by using ANSYS HFSS simulation software investigating the effect of antenna parameters. The results are as follows.

5.4.4.1 Effect of width ($P_w$) and length ($P_l$) of Inverted polygon slot

The notched band can be affected by varying the length and width of the proposed inverted polygon type slot. In this design, the bandwidth of the notched band depends on the width of the polygon type slot. The variation of the simulated VSWR curves with different slot widths ($P_w$) is as shown in Figure 5.23. As can be observed in Figure 5.23 that, a wider notched band can be achieved and shifted to the higher frequency side by increasing the slot widths from 0.65 mm to 1.12 mm. Figure 5.24 shows the variation of simulated VSWR with different slot lengths ($P_l$). It can be seen that, by increasing the slot lengths $P_l$ from 17.5 mm 19.5 mm, the center frequency of corresponding notched band will be shifted to the lower side. When $P_w$ is equal to 0.87 mm and $P_l$ is optimized at 18.5 mm, the desired notched band centered at 5.5 GHz is obtained to reject IEEE 802.11a WLAN or HIPERLAN/2 (5.15-5.91 GHz). Hence, the specific band-notched characteristics can be obtained by adjusting the slot length and width.

5.4.5 Measured radiation patterns of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA inverted polygon slot

The normalized radiation patterns of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA in far-field region, measured at 3.6, 5.5, 6.85 and 9.45 GHz are presented in Figure 5.25. From these radiation patterns it is seen that, the antenna exhibits nearly omnidirectional radiation characteristics in the H-plane and bidirectional radiation characteristics in E-plane.
5.4.6 Gain and radiation efficiency of the antenna

Figure 5.26 shows the simulated peak gain and efficiency of the 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA. The maximum peak gain and efficiency of the antenna is about 2.5 dB and above 95% for the UWB band. But the peak gain and efficiency decreases drastically at the vicinity of 5.5 GHz due to the band-notched function and, minimum gain and
Figure 5.25: Normalized radiation patterns in E-plane and H-plane of the proposed antenna at measured at (a) 3.6 GHz, (b) 5.5 GHz, (c) 6.85 GHz and (d) 9.45 GHz.
efficiency are observed as -4.3 dBi and 50% respectively. Outside the notched band, antenna gain and efficiency are almost stable throughout the UWB band is achieved. Hence, the antenna exhibits stable gain across the operation band and successfully performed with the rejection at IEEE 802.11a WLAN or HIPERLAN/2 (5.15-5.91 GHz).

Figure 5.26: Simulated peak gain and radiation efficiency of the antenna

5.4.7 Group delay of 5.15-5.91 GHz (IEEE 802.11a WLAN or HIPERLAN/2) band-notched truncated CDUMA

For UWB application, the investigation of the group delay variation is important and required. Pair of the identical antennas acts as the transmitting and receiving antennas which were positioned face to face orientation with a distance of 300 mm. Figure 5.27 depicts the simulated group delay variation of the antenna. It can be seen that, the variation of the group delay is within 1.5 ns across the operating UWB band, except at the rejected band of 5.5 GHz and the maximum group delay is observed more the 4 ns. Thus, it confirms that the antenna has a good time-domain characteristic.
5.5 Design of IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA with inverted polygon and inverted U slots

5.5.1 Geometry of the antenna

Figure 5.28 shows the antenna configuration and geometry of IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) band-notched truncated CDUMA. The physical geometry of the antenna structure is printed on the low cost commercially available FR-4 substrate material with thickness \( h \) of 1.6 mm, permittivity \( \varepsilon_r \) of 4.4 with loss tangent of \( \tan \delta \) 0.02 and a total size of antenna is 26 mm \( \times \) 32 mm. This antenna is composed of truncated disk radiating patch with an inverted U-shaped slot and inverted polygon shaped slot is fed by a simple 50\( \Omega \) CPW feed on the top surface and either side of the CPW feedline the partial ground planes are created. A small portion of the radiating patch is truncated all side to match the impedance matching for better impedance bandwidth for VSWR \( \leq 2 \). Further, to avoid an EM interference problem and achieve the
band-notched characteristics at 5.15-5.35 GHz and 5.725-5.825 GHz, an inverted polygon-shaped slot is etched on edge side of the radiating patch which creates a notch band at center frequency of 5.25 GHz. Further, in order to yield another notch band at the central frequency of 5.75 GHz the inverted U-shaped slot is created at the lower side of the radiating patch. By suitably tuning the lengths and widths of the inverted U-shaped and elliptical split ring slots the dual band-notches are adjusted respectively.

The antenna design model, simulation and optimized design are successfully done by using the Ansoft HFSS simulation software. The design parameters of the slots that affect the performance of the dual band-notched characteristics are investigated. By varying these parameters, the desired dual band-notches are obtained. The optimized design parameters of the proposed antenna are as follow: W = 26 mm, L = 32 mm, W_f = 3.07 mm, L_f = 15.15 mm, P_w & P_L = 0.43 mm & 17.5 mm, U_w & U_l = 0.5 mm & 16 mm, L_g = 14.5 mm, h = 1.6 mm, d = 0.65 mm and g = 0.36 mm. The photograph of this antenna is as shown in Figure 5.29 and antenna parameters measured using a Rohde & Schwarz ZVK model 1127.8651 German make Vector Network Analyzer (VNA).

Figure 5.28: Geometry of IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA
5.5.2 Measured and simulated VSWR characteristics

The measured and simulated VSWR versus frequency plots of the IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA is as shown in Figure 5.30. From the Figure 5.30, the proposed antenna meets the expectations of $VSWR \leq 2$ with good impedance bandwidth with covering the frequency range from 3 GHz to more than 14 GHz which covers the UWB (3.1 – 10.6 GHz) operating band excluding at 5.15-5.35 GHz and 5.725-5.825 GHz due to the creation of the individual slots on the radiating patch, the band-notches are produced at 5.25 GHz and 5.75 GHz respectively. By etching optimum dimensions of both inverted U-shaped and inverted polygon shaped on the upper and lower side of the radiating patch the dual notched bands are achieved. The performance of the antenna design the simulated VSWR, current distributions, radiation patterns, gain, radiation efficiency and group delay results of the dual band-notched antenna are presented and discussed in further sections.

5.5.3 Current distributions and 3D radiation patterns of IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA with inverted polygon and inverted U slots

Figure 5.31 shows the simulated surface current densities (A/m) and 3D radiation patterns of the IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA with inverted polygon and inverted U slots.
5.5.4 Parametric analysis of IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA with inverted polygon and inverted U slots

5.5.4.1 Effect of width $P_w$ and length $P_l$ of inverted polygon shaped slot

Figure 5.32 illustrates the simulated VSWR curves for different values of inverted polygon shaped slot widths ($P_w$). From this figure it is observed that,
the width of the inverted polygon shaped slot increases from 0.43 to 0.77 mm, the lower notch bandwidth is varied from 5.8 to 5.5 GHz. The simulated VSWR curves for different values of inverted polygon shaped slot lengths ($P_l$) is shown in Figure 5.33. When the length of the of the inverted polygon shaped slot increases from 17.5 to 19.9 mm, the center frequency of the lower notched band is varied
from 4.8 to 5.25 GHz. From these plots, we conclude that, the notch frequency
bandwidths at 5.15-5.35 GHz are controllable by varying the width and lengths of
the inverted polygon shaped slot. The optimum dimensions of inverted polygon
shaped slot are chosen as $P_w = 0.43$ mm and $P_l = 17.5$ mm.

![Figure 5.32: Simulated VSWR curves for the different values of $P_w$](image)

![Figure 5.33: Simulated VSWR curves for the different values of $P_l$](image)
5.5.4.2 Effect of lengths IU_w and IU_l of inverted U-shaped slot

The simulated VSWR versus frequency plots for different widths IU_w of the inverted U-slot is shown in Figure 5.34. From this figure, we can observed that, by increasing the IU_w values from 0.3 mm to 0.8 mm the center frequency, the upper notched band is also increasing from 5.42 to 6.10 GHz with other parameters of the antenna were kept constant. Similarly, Figure 5.35 shows the simulated VSWR versus frequency plots for different lengths IU_l of the inverted U-slot. From this figure, it is clear that, the center frequency of upper notched band is varied from 5.75 to 6.21 GHz by varying the IU_l from 14.4 mm to 16 mm. Thus, the parameters IU_w and IU_l shows influence on 5.75 GHz WLAN band which indicate that, the upper notched band mainly determine by the length IU_l and width IU_w of the inverted U slot. In order to confine the WiMAX 5.75 GHz WLAN the optimized design parameters such as IU_w = 0.5 mm, IU_l = 16 mm are the best choice.

![Simulated VSWR curves for the different values of IU_w](image.png)

*Figure 5.34: Simulated VSWR curves for the different values of IU_w*
5.5.5 Measured radiation patterns and gain of WiMAX (3.2-4.2 GHz) band-notched truncated DCUMA with inverted closed U-slot

Figure 5.36 shows the typical normalized far field E-plane (X-Z plane) and H-plane (Y-Z plane) radiation patterns of the antenna measured at the frequencies of 4 GHz, 5.35 GHz, 5.5 GHz and 5.75 GHz respectively. From these figures; it is clear that, the antenna gives nearly the omnidirectional radiation patterns in the H-plane (Y-Z plane) and bidirectional radiation patterns in E-plane (X-Y plane) at their corresponding frequencies over the entire UWB operating band.

5.5.6 Gain and radiation efficiency of WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA

The simulated peak gain and radiation efficiency of the antenna are shown in Figure 5.37. It can be seen that, there are dual band-notched characteristics occurring at the notched frequencies of 5.25 and 5.75 GHz, with the gains decreased to -3.8 dBi and -5.6 dBi and radiation efficiencies reduced to 10% and
Figure 5.36: Typical E-plane and H-plane radiation patterns measured at (a) 4 GHz, (b) 5.35 GHz and (c) 5.5 GHz, (d) 5.75 GHz and (e) 9.5 GHz
30% respectively.

Figure 5.37: Simulated peak gain and efficiency of the antenna

5.5.7 Group delay of WLAN (5.15-5.35 GHz and 5.725-5.825 GHz) dual band-notched truncated CDUMA

In the UWB antenna system, the time-domain characteristics are essential and variation of group delay should be a constant. Performance of antenna in time domain analysis is studied by setting a pair of identical antennas in face to face orientation. Figure 5.38 shows the variation of the group delay characteristics of the antenna. The group delay variation is constant, but at the dual notched-band, the group delay is changes less than 2.5 ns and 7 ns. The flat group delay to make sure that, the radiated phase signal response over UWB is linear. But the group delay variation is fluctuated which is observed around 7 GHz it is mainly due to impedance mismatching at the band-notched. Hence, all above characteristics shows that the antenna has a good dual notched bands performance over entire UWB band.
5.6 Design of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA with a pair of elliptical split ring slots

5.6.1 Geometry of the antenna

The geometry of the WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA is illustrated in Figure 5.39. The antenna design is fabricated on a low-cost FR-4 dielectric substrate having a relative permittivity ($\varepsilon_r$) of 4.4, loss tangent ($\tan\delta$) of 0.02 and a substrate thickness ($h$) of 1.6 mm. The proposed antenna is consists of a disk radiating patch with a pair of elliptical split-ring slots and a partial finite-size ground plane on either sides of the 50Ω CPW transmission line. The disk radiating patch with radius $R$ of 7.9 mm is further modified by truncating the side and top edges of the disk radiating element will form a proposed antenna structure. A truncating area with a size of $T_1 \& T_2 = 9.24$ mm and $T_3 = 11.9$ mm are maintained which provides a mechanism to enhance the impedance bandwidth with VSWR $\leq 2$ over the
UWB range. Moreover, in order to achieve an optimum impedance matching between a ground planes and 50Ω CPW microstripline the distance $g=0.37$ mm and distance $d=0.65$ mm is maintained between radiating patch and 50Ω CPW microstripline. The entire antenna structure is printed within a small size of $26 \times 32$ mm$^2$ substrate which represents a compact in its size.

A simple 50Ω CPW microstrip line feed with a length $L_f$ of 15.15 mm and $W_f$ of 3.07 mm is selected to excite the antenna. Further, to obtain WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual notched-band characteristics a pair of elliptical split-ring slots is loaded onto the radiating patch. With a slight change of total length of the elliptical split-ring slots, it is easy to adjust the center frequencies of the notched-bands at particular frequency ranges. Finally, optimized design parameters of the antenna are depicted as follows: $T_1 & T_2 = 9.24$ mm, $T_3 = 11.9$ mm, $e_{11}=26.06$ mm, $e_{12} = 19.09$ mm, $e_{1w}=0.61$ mm, $e_{2w}=0.65$ mm, $g=0.57$ mm, $d=0.65$ mm, $L_f=15.15$ mm, $W_f = 3.07$ mm, $L_g=14.5$ mm. The photograph of the top and bottom view of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA is given in Figure 5.40. A fabricated dual notched-band antenna has been constructed and tested successfully using Rohde & Schwarz ZVK model 1127.8651 German make Vector Network Analyzer (VNA). The performance results of the simulated and measured parameters such as voltage standing wave ratio (VSWR), radiation characteristics, surface current distributions, gain and antenna efficiency and group delay variation are discussed in following sections.

### 5.6.2 Measured and simulated VSWR characteristics

Figure 5.41 shows a comparison of measured and simulated VSWR curves of the WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA. From this figure, it can observe that, the measured VWSR is in good agreement with the simulated one. The impedance bandwidth of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA is coves the frequency range from 2.89 to more than 14 GHz for VSWR $\leq 2$ covering the entire UWB (3.1-10.6 GHz) frequency band with dual notched-bands of 3.2-3.88 GHz and 5.41-5.96 GHz which rejects the interference of WiMAX (3.2-3.88 GHz) and WLAN (5.725-5.825 GHz) systems.
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Figure 5.39: Geometry of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA

Figure 5.40: Photograph of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA
5.6.3 Current distributions and 3D radiation patterns of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA with a pair of elliptical split ring slots

In order to understand the radiation mechanism of the dual notched-band characteristics of the WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA, the simulated surface current flow at 3.4 and 5.75 GHz for the antenna which are illustrated in Figure 5.42. It can be observed from the Figure 5.42 (a) that, the surface current densities at 3.4 GHz is mainly distributing around the edges of the bigger size elliptical split-ring slot whereas the surface currents densities at 5.75 GHz is mainly accumulating along the edges of the lower size elliptical split-ring slot which is shown in Figure 5.42 (b). Also, from this figures it is well known that, the proposed antenna shows a dual notched-band feature at WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) within the UWB band. Further, the 3D radiation patterns which are measured at 3.3 GHz and 5.75 GHz also represent that, at the notched bands there is less energy is observed due to notch property.
5.6.4 Parametric analysis of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA with a pair of elliptical split ring slots

The parametric study of the WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA are analyzed to understand the dual notched-band characteristics by changing one parameter at a time and keeping other parameters as constant. The simulated results are obtained using the ANSYS high-frequency structure simulator (HFSS) simulation software. The following sub sections will discuss about the effect of various parameters of the proposed slots.
5.6.4.1 Effect of widths $e_{1w}$ and lengths $e_{1l}$ of bigger elliptical split-ring slot

Figure 5.43 exhibits the effect of the various bigger elliptical split-ring slot widths $e_{1w}$ on VSWR curves. A center notch frequency shift from 3.2 GHz to 3.4 GHz corresponds to the changing of the bigger elliptical split ring slot width from 0.61 mm to 1.22 mm. Figure 5.44 shows the VSWR curves of the presented antenna with different big elliptical split-ring slot lengths $e_{1l}$. As presented in Figure 5.43, it is observed that the central frequency of the notched band is controlled by the length of the elliptical split-ring slot. When the length of the elliptical split-ring slot varies from 22.64 mm to 27.57 mm the frequency shifts from around 3.2 to 3.65 GHz without disturbing the upper notched band.

![Simulated VSWR curves for the different values of $e_{1w}$](image)

*Figure 5.43: Simulated VSWR curves for the different values of $e_{1w}$*

5.6.4.2 Effect of widths $e_{2w}$ and lengths $e_{2l}$ of smaller elliptical split-ring slot

Similarly, the effect of simulated VSWR plots for different values of $e_{2w}$ is shown in Figure 5.45. As observed from this figure that, by increasing the width of the smaller elliptical split-ring slot values $e_{2w}$ from 0.54 mm to 1.07 mm and by keeping the $e_{2l}$ value is constant, the center frequencies of the corresponding notched-band shifts towards the lower frequencies of 5.6 GHz to 5.95 GHz. Figure
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5.46 shows the simulated VSWR plots for different values of $e_2_l$. By increasing the $e_2_l$ from 15.55 mm to 19.09 mm, the notch frequency is varied from 5.75 GHz to 6.8 GHz.

In addition, it is noticed from the above results that, the lengths and widths of the corresponding slots and by adjusting the one parameter keeping the other

![Simulated VSWR curves for the different values of $e_1_l$](image1)

**Figure 5.44:** Simulated VSWR curves for the different values of $e_1_l$

![Simulated VSWR curves for the different values of $e_2_w$](image2)

**Figure 5.45:** Simulated VSWR curves for the different values of $e_2_w$
parameters constant, only the corresponding notched band changes without disturbing the other notched-band. When total lengths of the slots are approximately equal to a half wavelength, the optimal notched-band characteristics can be achieved. The proposed antenna design the optimal values of the elliptical split-ring slots \( e_{1l} \), \( e_{1w} \), \( e_{2w} \) and \( e_{2l} \) are chosen as 0.61 mm, 26.06 mm, 0.65 mm and 19.09 respectively which approximately determines the center frequencies of the desired notched-bands of WiMAX (3.2-3.7 GHz) and WLAN (5.725-5.825 GHz).

**5.6.5 Measured radiation patterns of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA with a pair of elliptical split ring slots**

The measured E-plane and H-plane radiation patterns at 3.11 GHz, 4.5 GHz and 9.45 GHz are presented in Figure 5.47. From these figures it indicates that, the radiation patterns of the WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA at their corresponding frequencies, except rejected bands are stable and omnidirectional in the H-plane and bidirectional in the E-plane with its compact size.
Figure 5.47: Normalized typical E-plane and H-plane radiation patterns measured at (a) 3.11 GHz, (b) 4.5 GHz and (c) 9.54 GHz
5.6.6 Gain and antenna efficiency of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA

The simulated peak gains against frequency are presented in Figure 5.48. The gains varies from 4 dBi to 5.2 dBi for the UWB operating band, -2.8 dBi and -4 dBi for the rejected bands of WiMAX and WLAN range is obtained. Further, a 97% the antenna efficiency is observed and at the notched bands the radiation efficiencies reduced to 50% and 45% from first to second notched bands respectively. The presented result shows that, the proposed antenna is successfully performed with the rejection at 3.3 GHz WiMAX and 5.75 GHz WLAN.

![Figure 5.48: Simulated peak gain and antenna efficiency of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA](image)

5.6.7 Group delay of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA

Figure 5.49 shows the simulated group delay of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA. The variation of the group delay is within 1 ns throughout the UWB band except the dual
notched bands at 3.3 GHz and 5.75 GHz in which the maximum group delay is more than 4 ns and 7 ns respectively. The group delay corresponds well to the magnitude of transmission characteristics, which indicates that, the antenna has a good time-domain characteristic with small pulse distortion.

Figure 5.49: Group delay variation WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) dual band-notched truncated CDUMA

5.7 Design of triple band-notched truncated CDUMA

5.7.1 Geometry of the antenna

The geometry of the triple band-notched truncated CDUMA is as shown in Figure 5.50. The antenna is printed on a 26 × 32 × 1.6 mm³ FR-4 substrate material with dielectric constant $\varepsilon_r = 4.4$ with loss tangent ($\tan \delta = 0.02$ which is fed by simple 50Ω CPW transmission line. In Figure 5.50 the antenna composed a disk radiating patch which is truncated at the edges and three elliptical slot ring slots are placed at the middle of the radiating patch on the top surface of the substrate and pair of ground planes on either side of the CPW feedline. In this design the three elliptical slots are suitably embedding into the middle of the radiating
patch which generates triple band-notched characteristics at WiMAX (3.3-3.7 GHz) and IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz). Further in this design, the band-notched characteristic is controllable by changing the dimensions of the elliptical slots.

The proposed antenna is simulated and optimized by successfully using the HFSS simulating software. The some design parameters of the proposed antenna that affect the band-notch characteristic are analyzed. The optimized parameters of the triple band-notch truncated CDUMA are: e1 = 29 mm, e2 = 19.33 mm, e3 = 15.6, g = 0.57 mm, d = 0.65 mm, Lf = 15.15 mm, Wf = 3.07 mm, Lg = 14.5 mm. The manufactured triple band-notched truncated CDUMA is shown in Figure 5.51.

![Figure 5.50: Geometry of the triple band-notched truncated CDUMA](image)

5.7.2 Measured and simulated VSWR characteristics

The measured and simulated VSWR curves of the triple band-notch truncated CDUMA are as shown in Figure 5.52. From this figure, it is observed that, the impedance bandwidth for VSWR ≤ 2 covers the 2.91 to more than 14 GHz...
with triple notched bands for VSWR > 2 covering WiMAX (3.3-3.7 GHz) and IEEE 802.1a/b/g WLAN (5.15-5.35 GHz and 5.725-5.825 GHz). The measured VSWR result is reasonably agrees with the simulated one. However, the proposed antenna is suitable for UWB applications with triple notched bands at 3.5 GHz WiMAX and WLAN (5.15-5.35 GHz) and WLAN (5.725-5.825 GHz) respectively.
5.7.3 Current distributions and 3D radiation patterns of triple band-notched truncated CDUMA

In order to investigate the EM mechanism of the triple band-notched operation, the surface current distributions and 3D radiation patterns of the triple band-notched truncated CDUMA studied at the center frequencies of the three notched bands which are presented in Figure 5.53. It can be observed from these figures that, the current is mainly distributed on the edges of the three corresponding elliptical split ring slots at 3.3 GHz, 5.15 GHz and 5.7 GHz respectively. The proposed elliptical split ring slots act as good half-wave and full-wave resonators respectively which results into the triple band-notched characteristics. Further, the 3D radiation patterns of the antenna at notched frequencies are measured at 3.27, 5.15 and 5.75 GHz. The radiation patterns at these frequencies are omnidirectional in nature. Radiation energy is substantially smaller at 3.27, 5.15 and 5.75 GHz, and are distorted.

5.7.4 Realization of Triple band-notched characteristics with individual band rejection elements

To understand the realization triple band-notched characteristics, individual VSWR plots for each elliptical split ring slots of triple band-notched truncated CDUMA with an individual band-notched component have been discussed and presented in Figure 5.54.

The realization of the triple band-notched characteristics with individual band rejection elements, the simulated VSWR versus frequency plots for the individual slots and without slots on the radiating patch is as shown in Figure 5.54. From Figure 5.54 (a), the antenna meet the expectations of VSWR ≤ 2 with better impedance bandwidth with wideband from 2.82 to more than 14 GHz which covers the UWB (3.1 – 10.6 GHz) frequency band. From the Figure 5.54 (b)-(d), due to the creation of the individual elliptical split ring slots on the radiating patch the notch bands are produced at 3.3 GHz, 5.15 GHz and 5.7 GHz respectively. The band-notched characteristics near 3.3 GHz is mainly due to the etching the bigger elliptical split ring slots at the upper side of the radiating patch with optimum parameter dimensions chosen as $e_{1w} = 0.50$ mm, $e_1 = 29$ mm. Another band-
Figure 5.53: Surface current distributions of triple band-notched truncated CDUMA observed at the frequencies of (a) 3.27 GHz (b) 5.15 GHz and (c) 5.7 GHz.

The notched characteristic at 5.15 GHz which is shown in Figure 5.54 (c) is produced due to the creation of the elliptical split ring slot $e_2$ at the middle of the radiating patch and optimum parameter dimensions of the elliptical split ring slot as chosen are $e_2W = 0.50$ mm and $e_2l = 19.50$ mm. Further, the third band-notched characteristics near 5.75 GHz is obtained by etching the smaller elliptical split ring slot $e_3$ at the lower side of the radiating patch with optimum dimensions chosen as $e_3W = 0.50$ mm, $e_3l = 15.8$ mm. In Figure 5.54 (d), it is clear that by embedding the all elliptical split ring slots on the radiating patch the triple
Figure 5.54: Realization of triple band-notched characteristics with individual band rejection elements (a) Simulated VSWR plot for without slots, (b) Simulated VSWR plot for elliptical split ring slot e1, (c) Simulated VSWR plot for elliptical split ring slot e2, (d) Simulated VSWR plot for elliptical split ring slot e3 and (e) Simulated VSWR plot for elliptical split ring slots e1, e2, e3

band-notched characteristics are realized at 3.3 GHz, 5.25 GHz and 5.75 GHz which avoids the interference of WIMAX (3.3 – 3.8 GHz) and WLAN (5.15 –
5.35 GHz) and WLAN (5.725-5.825 GHz) frequency bands respectively.

5.7.5 Measured radiation patterns triple band-notched truncated CDUMA

The typical measured $E$-plane and $H$-plane radiation patterns of triple band-notched truncated CDUMA are measured at 2.88, 6.5 and 7.5 GHz which is illustrated in Figure 5.55. Both co-polar and cross-polar have been shown. The $H$-plane radiation patterns are almost omnidirectional for all respective frequencies. The $E$-plane radiation patterns are donut shaped in nature.

5.7.6 Gain and efficiency of triple band-notched truncated CDUMA

The peak gain and radiation efficiency of triple band-notched truncated CDUMA are presented in Figure 5.56. From this figure, it is indicates that, the antenna without elliptical split ring slots exhibits stable gain of 4 dBi. When the elliptical split ring slots are loaded, the gain suddenly decreased to -5.5 dB at 3.3 GHz, -2.6 dB at 5.25 GHz and -3.1 dBi at 5.75 GHz with degraded efficiencies of 45% and 30% at respective stop bands. But, triple band-notched truncated CDUMA shows a 4 dBi stable gain and 87% efficiency throughout the UWB range. Thus, the antenna which shows the UWB characteristics with triple band notched performance.

5.7.7 Group delay of triple band-notched truncated CDUMA

In UWB systems the time domain characteristics is the important feature in transmitting and receiving the short pulses. Hence, in order to understand the time-domain performance, group delay characteristics of triple band-notched truncated CDUMA has been simulated between two identical prototype antennas in face-to-face orientation with keeping distance 300 mm between them. Figure 5.57 shows a group delay of response of triple band-notched truncated CDUMA. A constant delay is less than 15 ns are observed throughout the UWB operating band except in the notched bands, the group delay is observed as 3.5 ns, 5 ns and 5.3 ns are observed at 3.3, 5.25 and 5.75 GHz respectively. This phenomenon represents the triple band-notched truncated CDUMA exhibits a good time-domain
Figure 5.55: Measured radiation patterns of triple band-notched truncated CDUMA measured at (a) 2.8 GHz, (b) 6.5 GHz and (c) 7.5 GHz
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Figure 5.56: Gain and efficiency of triple band-notched truncated CDUMA characteristics for linear pulse transmission.

Figure 5.57: Group delay of triple band-notched truncated CDUMA

The conclusions drawn from the detailed experimental and simulation investigations carried out in this research work are presented in chapter 6. Some key
contributions of presented outcomes and the future directions for further related investigation is also highlighted in this chapter.