Chapter 4

Investigation on planar UWB microstripline-fed monopole antenna

4.1 Introduction

This chapter deals with the investigation on planar UWB microstripline-fed monopole antennas with single, dual, triple and quad band-notched characteristics. The novel approach for design and development of various compact microstripline-fed UWB monopole antennas with single, dual, triple and quad band-notched characteristics are explained in this chapter. A detailed explanations is given on the study which is conducted on the disk UWB monopole antenna modifying the disk radiating patches i.e. truncating the side edges of the radiating patch and creating small notch at top center of the ground plane

A part of this chapter is published in the peer reviewed Journals

to make antenna compact in its size. The impedance matching, providing the large impedance bandwidth and easily covers the FCC UWB operating frequency band of 3.1 to 10.6 GHz is explained. Further, to prevent the potential interference problem by rejecting the narrow operating bands existing over the UWB band of 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 (7.25-7.75 GHz), ITU band (8.01-8.5 GHz), the different wavelength sized slots, strips and parasitic patches are embedded on radiating patches. Detailed results and discussion for various optimized antenna parameters and parametric analysis are also included in this chapter. The VSWR, omnidirectional radiation patterns, current distributions, peak gain plots, group delay variation plots and photographs of fabricated antennas are also shown in this chapter.

4.2 Planar disk microstrip-line-fed UWB monopole antenna (PDMUMA)

4.2.1 Geometry of the PDMUMA

The top and side view configuration of the proposed antenna is as shown in Figure 4.1 (a). The antenna consists of a circular radiating patch of radius \( a = 10.7 \text{ mm} \) is fed by a simple 50\( \Omega \) microstrip-line feed on the substrate and a partial ground plane is composed at the bottom side of the substrate. It is designed on the low-cost FR-4 epoxy substrate material with relative permittivity of 4.4, thickness of 1.6 mm and a tangential loss \( \tan \sigma \) of 0.02. The antenna is occupies on the substrate material with an area of \( L \times W = 32 \times 26 \text{ mm} \). The antenna has a 50\( \Omega \) microstrip-line feed of width \( W_f = 3.068 \text{ mm} \) and length \( L_f = 15.15 \text{ mm} \) is used. On the bottom side of the substrate a partial conducting ground plane of length \( L_g = 14 \text{ mm} \) and \( d = 1.15 \text{ mm} \) is the distance between feed point of the circular radiating patch and the bottom ground plane. A rectangular notch with a size of \( N_L \times N_W = 3.2 \times 4 \text{ mm} \) is designed on the mid top of the ground plane that provides a mechanism to enhance the impedance bandwidth with -10 dB return loss over the UWB range. At the tip of microstrip-line feed a microwave source is assigned. The top and bottom view photographs of the PDMUMA is shown in Figure 4.1 (b). The optimal dimensions of the PDMUMA are shown in Table-4.1.
Table 4.1: The optimal dimensions of PDMUMA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>W</th>
<th>L</th>
<th>a</th>
<th>Wf</th>
<th>Lf</th>
<th>Lg</th>
<th>d</th>
<th>NL &amp; NW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (mm)</td>
<td>32</td>
<td>26</td>
<td>7.9</td>
<td>3.068</td>
<td>15.15</td>
<td>14</td>
<td>1.15</td>
<td>3.2 &amp; 4</td>
</tr>
</tbody>
</table>

Figure 4.1: Geometry of the planar disk microstripline-fed UWB monopole antenna (PDMUMA) and photographs of the fabricated antenna
4.2.2 Return loss characteristics of the PDMUMA

Figure 4.2 shows the measured and simulated return loss versus frequency plot of PDMUMA with optimal design dimensions. From this figure it is clear that, the antenna exhibits a return loss curve which is less than -10 dB lies from 3.1 to more than 14 GHz with three resonant frequencies centered at 4.30 GHz, 6.80 GHz and 10.6 GHz respectively. From this figure it is also clear that, there is a very well agreement between the measured and simulated results. The desired ultra-wideband is produced due to modified partial truncated ground plane structure i.e. creating a rectangular slot cut and for the better performance of the impedance matching the gap \((d)\) between radiating patch and the ground plane which is kept constant at 0.5 mm.

![Figure 4.2: Measured and simulated variation of return loss versus frequency curve of PDMUMA with optimal design parameters](image)

4.2.3 Parametric analysis of the PDMUMA

In order to understand the effect of proposed antenna the various parameters are analyzed by conducting parametric study with the help of simulation software. All the simulations are carried out using ANSYS HFSS software. It is seen from the various simulation results, we may study the effect of monopole antenna by varying the parameters such as \(L_g\), \(W\), \(L_f\) and \(N_L\) which are quite effective for improving the antenna performance. The present parametric analysis is influenced by studying the initial design presented in [70]. A detail of the
parametric study along with concluding remarks of each parameter is discussed in the following sections.

4.2.3.1 Effect of ground plane length $L_g$

The effect of ground plane length $L_g$ is studied and illustrated in Figure 4.3. First by varying the ground plane lengths $L_g$ increasing from 13 mm to 14.5 mm the slight variations in lower cut-off frequency is observed and also impedance bandwidth is significantly changing with multi peak resonances at 4.30 GHz, 6.80 and 10.6 GHz. The optimal value of $L_g$ is found be at 14 mm for better impedance matching where we get desired maximum -10 dB return loss which covers the frequency range from 2.42 to more than 14 GHz and gives maximum impedance bandwidth of 141%. This indicates that $L_g$ is the parameter to change the impedance matching of antenna.

![Figure 4.3: Variation of return loss versus frequency curve for different ground plane lengths $L_g$ of PDMUMA](image)

4.2.3.2 Effect of ground plane width $W$

Figure 4.4 shows the variation of return loss versus frequency curves for different widths $W$ of bottom ground plane. From this figure it is observed that, the resonant frequencies with minimum return loss is observed by increasing the ground plane widths from 25 mm to 26.5 mm. Therefore, when $W = 26.5$ mm the
antenna gives a minimum return loss of -34 dB at 4.85 GHz. Hence, \( W \) is also one of the parameter to change the impedance matching with maximum impedance bandwidth of the antenna.

![Variation of return loss versus frequency curve for different widths W of the ground plane of PDMUMA](image)

**Figure 4.4: Variation of return loss versus frequency curve for different widths W of the ground plane of PDMUMA**

### 4.2.3.3 Effect of microstripline feed length \( L_f \)

The other parameter of the proposed antenna i.e. length of the microstripline feed \( L_f \) is also effective in enhancing of the impedance bandwidth. Figure 4.5 shows the variation of return loss versus frequency curves with optimal designs of different length of microstripline feed \( L_f \) when \( W \) is fixed at 26 mm. It is seen from Figure 4.5 that, by increasing the length of the microstripline feed from 14.05 mm to 15.15 mm the variation in impedance bandwidths with minimum return loss is observed. Hence when \( L_f \) is 15.15 mm antenna gives minimum return loss of -46 dB at 4.85 GHz. Therefore better impedance bandwidth and impedance matching is found when \( L_f = 15.15 \) mm.

### 4.2.3.4 Effect of rectangular slot cut length and width (\( N_L \) and \( N_W \))

Figure 4.6 and 4.7 shows the simulated return loss variation plots for different slot cut length (\( N_L \)) and width (\( N_W \)) in the ground planes. It can be seen that by varying the rectangular cut slot \( N_L \) and \( N_W \) from \( N_L = 3.2 \) to \( 4.2 \) mm and \( N_W = 3.4 \) to \( 4.2 \) mm respectively, the antenna possess better impedance matching and
hence enhance the impedance bandwidth with -10 dB return loss over the UWB range. A rectangular notch with a size of $N_L \times N_W = 3.2 \times 4$ mm is chosen as optimal dimensions.

Figure 4.5: Variation of return loss versus frequency curve for different length of the microstripline feed $L_f$ of PDMUMA

Figure 4.6: Variation of return loss versus frequency curve for different rectangular notch cut $N_W$ of PDMUMA
Figure 4.8 (a)-(c) shows the distribution of the current density on the surface and 3D radiation patterns of PDMUMA measured at 4.30, 6.80 and 10.60 GHz for the optimal design parameters. From these figures, it is clear that, the current is mainly distributing at the edge feed point of the circular radiating patch. From Figure 4.8 (a) and (b) it is seen that, the current is uniformly distributing towards the edge of the radiating patch and that gives the fundamental and second resonant frequencies which is dependent to the radius of the circular radiating patch and large surface current density is observed along the microstripline feed, while in Figure 4.8 (c) the weak surface current distribution is observed along at the edge of the radiating patch. At the first (4.30 GHz) and second (6.80 GHz) resonant frequencies nearly omni-directional radiation patterns are obtained but at third (10.60 GHz) resonant the corresponding pattern is losing its omnidirectional characteristics due to ground plane involvement to this resonance.

4.2.5 Measured radiation patterns of the PDMUMA

The typical radiation patterns of PDMUMA measured in E- and H-planes at 3.60, 4.70, 5.5, and 7.5 GHz are shown in Figure 4.9 (a)-(d) respectively. From these figures it is clear that, the antenna gives nearly omnidirectional radiation
Figure 4.8: Simulated current distributions and 3D radiation patterns of PDMUMA measured at (a) 4.30 GHz, (b) 6.80 GHz and (c) 10.60 GHz characteristics in its operating band from 3.1 to 10.6 GHz. However, at the higher frequencies, the radiation patterns are slightly distorted.

4.2.6 Gain of the PDMUMA

The measured gain of PDMUMA plotted from 3 to 14 GHz which is shown in Figure 4.10. From this figure, it is observed that, over the UWB operating band, the stable peak gain of 2.5 - 5.2 dB is observed.
Figure 4.9: Measured radiation patterns in E- and H-plane of PDMUMA measured at (a) 3.6 GHz, (b) 4.70 GHz, (c) 5.5 GHz and (d) 7.5 GHz
4.2.7 Group delay of the PDMUMA

In order to ensure the time-domain characteristics, the group delay variation of PDMUMA is simulated between two identical prototype antenna models in the face-to-face orientation with keeping distance 300 mm as proposed in the software between them. Figure 4.11 shows a group delay variation of PDMUMA. A constant delay is less than 1 ns are observed throughout the UWB operating band except in the notched bands. This phenomenon represents the antenna exhibits an excellent time-domain characteristics for linear transmission.

![Figure 4.10: Gain of PDMUMA](image)

![Figure 4.11: Group delay for the face to face orientation in the time domain of PDMUMA](image)
4.3 Planar stepped semi disk base triangular slot cut microstripline-fed UWB monopole antenna (PSSDTMUMA) with enhanced impedance bandwidth

In the previous section, we have investigated a parametric analysis of planar disk microstripline-fed UWB monopole antenna (PDMUMA). It is observed that, the antenna shows moderate impedance bandwidth and poor radiation patterns especially at higher frequencies. In this section, for enhancing the impedance bandwidth the conventional antenna is modified through evolution to get an optimized antenna design with enhanced impedance bandwidth and details of the geometries and their parametric study is discussed in the following sections.

4.3.1 Evolution of the PSSDTMUMA

The geometry and its configuration of PSSDTMUMA antenna is printed on commercially available modified glass epoxy dielectric substrate with a relative permittivity ($\varepsilon_r$) of 4.2, tangential loss (tan $\delta$) of 0.02 and thickness (h) of 1.6 mm. The overall size of the antenna including bottom ground plane is $35 \times 50 \text{ mm}^2$. The arch shaped radiating element which is modified from the conventional circular radiating patch having actual radius ‘$a$’ which is shown in Figure 4.1. Figure 4.12 shows the antenna evolution of PSSDTMUMA. This antenna design starts with a conventional microstripline fed disk monopole antenna. The design of PSSDTMUMA is discussed in various modifications such as planar semi disk base microstripline-fed UWB monopole antenna (Antenna-I), planar stepped semi disk base microstripline-fed UWB monopole antenna (Antenna-II) and planar stepped semi disk base triangular slot cut microstripline-fed UWB monopole antenna PSSDTMUMA (Antenna-III). The parametric study of Antenna-I, Antenna-II and Antenna-III are discussed in the following sections.

4.3.1.1 Planar semi disk base microstripline-fed UWB monopole antenna (Antenna-I)

The geometry of the proposed planar semi disk base microstripline-fed UWB antenna is illustrated in Figure 4.13. This antenna is fabricated on a low-cost FR-4 substrate having a relative permittivity ($\varepsilon_r$) of 4.4, loss tangent (tan $\delta$) of
Figure 4.12: Evolution of PSSDTMUMA (a) planar semi disk base microstripline-fed UWB monopole antenna (Antenna-I), (b) planar stepped semi disk base microstripline-fed UWB monopole antenna (Antenna-II) and (c) planar stepped semi disk base triangular slot cut microstripline-fed UWB monopole antenna (Antenna-III)

0.02 and a substrate thickness of 1.6 mm. The antenna is composed of a semi disk base radiating patch with a side edge truncation and a partial finite-size ground plane on a bottom side of the substrate. The semi disk base radiating element is basically a modified geometry of a conventional disk shape with radius ‘a’ of 7.9 mm which is shown in Figure 4.13. Further, the side edges of the circular radiating patch are truncated which will form a Antenna-I structure. A rectangular notch with a size of $N_L \times N_W = 3.2 \times 4$ mm is created on the top middle of the ground plane that provides a mechanism to enhance the impedance bandwidth with VSWR = 2 over the UWB range.

Figure 4.13: Geometry of planar semi disk base microstripline-fed UWB antenna (Antenna-I)
Moreover, in order to achieve an optimum impedance matching between a radiating patch and microstripline the distance $g=1.15$ mm is maintained. The entire antenna structure is printed within a small size of $26 \times 32$ mm$^2$ substrate which represents a compact size in its structure. For the present analysis a simple 50Ω microstripline feed with a length $L_f$ of 15.15 mm and $W_f$ of 3.06 mm is selected to excite the antenna. A semi miniature-A (SMA) connector has been used at the tip of 50Ω microstripline feed for feeding the microwave power. Top and bottom side photographs of the Antenna-I i.e. planar semi disk base microstripline-fed UWB antenna is as shown in Figure 4.14.

![Figure 4.14: Top and bottom side photographs of planar semi disk base microstripline-fed UWB antenna (Antenna-I) (Image)](image)

Figure 4.15 illustrates the return loss versus frequency plot of planar semi disk base microstripline-fed UWB antenna. From this figure, it can be observed that, the impedance bandwidth covers the frequency range from 3.05 to more than 16 GHz with the magnitude of return loss less than -10 dB with two resonant frequencies at 4.70 GHz and 7.22 GHz.

4.3.1.2 Simulated current distributions and 3D radiation patterns of Antenna-I

Further to understand the resonance mechanism of the planar semi disk base microstripline-fed UWB antenna can be explained by analysing the current distributions and radiation patterns of the antenna at resonances frequencies of 4.70 GHz and 7.20 GHz which are shown in Figure 4.16 (a)-(b) respectively. It can be found in case of first resonant frequency the maximum current is observed along the microstripline and the radiating patch and radiation pattern at this frequency
is nearly omnidirectional. But at the second resonance the microstripline feed and some of the ground plane portion is contributed and hence the radiation pattern is found to be partially distorted.

4.3.1.3 Effect of ground plane length $L_g$

Figure 4.17 shows the return loss variation with different ground plane lengths in Antenna-I. It is found that, for the ground plane lengths $L_g$ values for 13.2 mm to 13.6 mm, there is no peak resonances are observed but for the $L_g$ values of 13.8 mm, 14 mm and 14.2 mm result in the two resonant modes at 4.70 GHz, and 7.22 GHz with wide impedance bandwidth is obtained. The value of $L_g$ is found be at 14 mm for better impedance matching where we get desired minimum -10 dB return loss ($S_{11}$) of -55 dB.

4.3.2 Planar serrated semi disk base microstripline-fed UWB monopole antenna (Antenna-II)

Geometry of this planar serrated semi disk base microstripline-fed UWB monopole antenna is shown in Figure 4.18. Serrated semi disk base structure is formed by truncating the radiating patch edges of $T_1$, $T_2$ and $T_3$ from a normal disk patch. Further, to enhance the impedance bandwidth the serrations are made to the opposite side of $T_3$ which forming a staircase configuration. Creating
Figure 4.16: Current distributions and 3D radiation patterns of the Antenna-I observed at (a) 4.70 and (b) 7.22 GHz

Figure 4.17: Simulated return loss versus frequency plots for different values of \( L_g \) Antenna-I
serrations to the radiating patch are aimed to change the distance between the radiating patch and the ground plane in order to tune the coupling between the radiating patch and ground plane makes the antennas to give the wide impedance bandwidth. Top and bottom side photographs of the proposed planar semi disk base microstripline-fed UWB antenna is as shown in Figure 4.19.

![Figure 4.18: Geometry of the planar serrated semi disk base microstripline-fed UWB monopole antenna( Antenna-II)](image)

![Figure 4.19: Top and bottom side photographs of planar semi disk base microstripline-fed UWB antenna (Antenna-II)](image)

Figure 4.20 depicts the return loss versus frequency plot of Antenna-II. It can be shown that, the impedance bandwidth covers the frequency range from 3.1 to more than 18 GHz for the magnitude of return loss less than -10 dB with three resonant frequencies centered at 3.4 GHz, 5.6 GHz and 9 GHz.
4.3.2.1 Simulated current distributions and 3D radiation patterns of the Antenna-II

The typical vectored current distributions on Antenna-II at three resonant frequencies at 3.4 GHz, 5.6 GHz and 9 GHz are plotted in Figure 4.21. It is observed from the figures, that the current is mainly flowing through serrated edges and along the microstripline feed. At the first two resonant frequencies the current distributions reveal that, the antenna shows an almost omnidirectional radiation patterns. But at the third resonance frequency the patterns is slightly distorted.

4.3.2.2 Effect of ground plane length $L_g$

Variation of return loss with different ground plane lengths of Antenna-II is as shown in Figure 4.22. It is observed that, increasing the $L_g$ values from 13.2 mm to 14.22 mm, three resonance frequencies are obtained and the enhancement of impedance bandwidth is also achieved. When value of $L_g = 14$ mm the antenna gives highest impedance bandwidth which is 145%. This value of $L_g$ is chosen as optimum for getting highest impedance bandwidth for -10 dB return loss.
4.3.3 Planar stepped semi disk base triangular slot cut microstripline-fed UWB monopole antenna (Antenna-III)

In the previous sections we have studied a design and development of planar semi disk base microstripline-fed UWB monopole antenna (Antenna-I) and planar stepped semi disk base microstripline-fed UWB monopole antenna (Antenna-II). It is observed from the Antenna-II that, making serrations on the bottom edges
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4.3.3.1 Geometry of the Antenna-III

The antenna configuration with optimized dimensions of planar stepped semi disk base triangular slot cut microstrip-line-fed UWB monopole antenna (Antenna-III) is as shown in Figure 4.23. This antenna structure is printed on a 1.6 mm thick modified glass epoxy dielectric substrate of permittivity ($\varepsilon_r$) 4.2 and loss tangent ($\delta$) 0.02. The entire size of the antenna is 26 mm $\times$ 32 mm. The antenna is formed by modifying the circular radiating patch and is fed by simple 50Ω microstrip-line and this feedline is connected to SMA connector for excitation. In this design we selected a truncated circular radiating patch which is selected because it is acceptable for omnidirectional radiation. The total radius of the modified circular patch is $a = 7.9$ mm. Bottom of the antenna structure the asymmetric partial ground plane of 20 mm $\times$ 15 mm with small rectangular slot cut dimensions of $N_L \times N_W = 3.2 \times 4$ mm is created. For performance of the impedance bandwidth, the gap ($d$) between radiating patch and the ground plane is kept constant at 4 mm. The wide rectangular slots are embedded at the side edges of the ground plane for impedance matching. To improve the impedance bandwidth, the triangular shape slot cut area of 25 mm is embedded on the top of the truncated disk radiating patch to forming a staircase modified structure which enhances the impedance bandwidth. Further, with the aim of designing desired UWB antenna with compact size and enhanced impedance bandwidth, the triangular shape slot cut is embedded on the top of the radiating patch.

Figure 4.22: Simulated return loss versus frequency plots for different values of $L_g$ of Antenna-II

of the truncated disk radiating patch to forming a staircase modified structure which enhances the impedance bandwidth. Further, with the aim of designing desired UWB antenna with compact size and enhanced impedance bandwidth, the triangular shape slot cut is embedded on the top of the radiating patch.
of the radiating patch and this structure makes antenna compactness in its size reduced by 28% when compared to Antenna-I and gives improved impedance bandwidth. The corresponding photograph of the Antenna-III is shown in Figure 4.24.

![Geometry of the Antenna-III](image)

*Figure 4.23: Geometry of the Antenna-III*

![Top and bottom side photographs of the planar semi disk base microstrip-fed UWB antenna (Antenna-III)](image)

*Figure 4.24: Top and bottom side photographs of the planar semi disk base microstrip-fed UWB antenna (Antenna-III)*

### 4.3.3.2 Experimental and simulation return loss characteristics

The Antenna-III is simulated using EM 3D full-wave Ansoft HFSS. The fabricated antenna is experimentally measured using Rohde & Schwarz ZVK model 1127.8651 German make Vector Network Analyser (VNA).
Figure 4.25 shows the experimental and simulated return loss versus frequency plots of the Antenna-III. In Figure 4.25, the antenna meet the expectations of the magnitude of the return loss is less than -10 dB (|S_{11}| < -10 dB) covers the 3.1 to more than 20 GHz. From this figure it is also clear that, there is a qualitative agreement between the experimental and simulated results.

![Experimental and simulated return loss versus frequency of Antenna-III for the optimized dimensions](image.png)

*Figure 4.25: Experimental and simulated return loss versus frequency of Antenna-III for the optimized dimensions*

### 4.3.3.3 Current distribution and 3D radiation pattern of Antenna-III

Figure 4.26 shows the magnitude of the surface vector current densities of Antenna-III at measured frequencies 4.23 GHz, 8.80 GHz and 11 GHz for the optimized design parameters. From Figure 4.26 (a), we can observe that, the more density of current is mainly distributed along the microstrip line feed and corresponding 3D radiation plots which shows an almost omni-directional radiation characteristics but at higher resonance frequency of 11 GHz which is shown in Figure 4.26 (c), the less current flow is observed on the radiating patch and heavy currents are observed on the ground plane, hence the radiation pattern is narrowly distorted.
4.3.3.4 Measured radiation patterns of the Antenna-III

Figure 4.27 shows the normalized co-polar and cross-polar radiation patterns in E-plane and H-plane of the Antenna-III measured at the frequencies of 4.23 GHz, 8.80 GHz and 11 GHz respectively. From these figures, it is seen that nearly omnidirectional radiation patterns in the E-plane and dipole like bidirectional radiation patterns in H-plane are obtained.
Figure 4.27: Normalized co- and cross-polar radiation patterns in E-plane and H-plane of antenna-III measured at (a) 4.23 GHz, (b) 8.80 GHz and (c) 11 GHz
4.3.3.5 Parametric Analysis of the Antenna-III

The parametric study is carried out to optimize the Antenna-III and this provides a more information about the effectiveness of the antenna design parameters in simulation software.

4.3.3.5.1 Effect of finite ground plane length ($L_g$): Figure 4.28 shows the simulated return loss versus frequency plot for the various values of $L_g$. From this figure it is clear that, the impedance bandwidth is effectively improved when varying the ground plane lengths $L_g$ increasing from 13.2 mm to 14.2 mm. Thus for the UWB operation with improved impedance bandwidth for the magnitude of -10 dB return loss the optimized value of $L_g$ is found be at 14 mm. For this value antenna gives highest impedance bandwidth of 149%.

![Figure 4.28: Return loss versus frequency of Antenna-III for different values of $L_g$](image)

4.3.3.5.2 Effect of finite ground plane length ($W$): Figure 4.29 shows the variation of return loss versus frequency curves for different widths $W$ of bottom ground plane of antenna-III. It is observed that, there are three resonant frequencies with minimum return loss when varying the ground plane widths from 25 mm to 26.5 mm. From this figure, it is also evident that, at $W = 25$ mm, 25.5 mm and 26.5 mm the antenna showing a three resonant frequencies but at the higher frequencies the lesser return loss variation is observed. Hence for UWB
operation, $W$ is fixed at 26 mm as an optimum dimension. For which antenna gives highest impedance bandwidth of 149%.

![Variation of return loss versus frequency curve for different widths of $W$ of the ground plane of Antenna-III]

**Figure 4.29**: Variation of return loss versus frequency curve for different widths of $W$ of the ground plane of Antenna-III

### 4.3.3.6 Gain

Figure 4.30 gives the realized gains of Antenna-III with and without elliptical ring slot within its operating frequency. From this figure it is clear that the nearly stable realized gain of the antenna ranges from 3 dB to 4 dB is observed over the entire UWB band except at the 3.1 GHz to 5.11 GHz and are about -8 dB at the vicinity of rejection band.

### 4.3.3.7 Time domain analysis of Antenna-III

Group delay of the antenna system transfer function of Antenna-III is depicted in Figure 4.31. This is a critical parameter for UWB antenna which measures the time signal distortion introduced by the antenna. The group delay function is measured by using two identical antenna prototypes placed with a distance of 300 mm. As observed from the Figure 4.31, a small group delay variation between 1 ns fluctuation across the UWB operating band is achieved. Which is the acceptable range for any good design.
4.4 Band-notched characteristics of the microstripline-fed UWB monopole antennas

On February 14, 2002 the Federal Communication Commission (FCC) of United State has released a First Report and Order regarding the Ultra-Wideband (UWB) [121]. This Commission regulates and authorized the unlicensed exert of UWB communication technology within the range of 3.1 to 10.6 GHz frequency band for low and high data rate personal area network (PAN) wireless devices,
long distance range, radar and imaging systems. Over the past ten years, the UWB is receiving much attention and has experienced impressive technological developments for wireless connectivity high tech gadgets because of their significant features such as secure short range high-speed data transmission rate, large impedance bandwidth, short-range wireless characteristics, data securable, inexpensive, low power consumption and sensible design [122]. The antenna engineers are facing many critical challenges while designing UWB antennas for short-range wireless communication. The planar printed monopole antennas are most promising candidate for UWB applications since they exhibit very attractive features such as large operating impedance bandwidth, simple in structure, omni-directional radiation patterns, low cost, easy to fabricate, integration with small wireless terminals etc. For the reliable usage and the desired requirement of UWB communications systems, the responsible component is UWB antenna which is considered as current research interest and must meet the requirement of high impedance bandwidth and omnidirectional radiation characteristics with stable gain over the entire UWB antenna. Recent studies reveal that, the UWB antenna engineers have been proposed a lot of printed monopole antenna configurations such as circular, square, circular slot, elliptical, rectangular etc. for ultra-wideband applications with omnidirectional radiation patterns with stable gain [65; 70; 123; 124; 125; 126].

Despite all the advantages of UWB technology over the 3.1-10.6 GHz communication system there exist an electromagnetic interference (EMI) problem with coexisting narrow frequency band such as IEEE 802.11b worldwide interoperability for microwave access WiMAX (3.3-3.7 GHz), C-band satellite communication system (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 (7.25-7.75 GHz), ITU band (8.01-8.5 GHz). To overcome the problem of interference the band-notched property is most adoptable technique to solve these potential problems.

Recently, the numerous UWB antennas with single, dual and multi notch-band characteristics have been reported [87; 127; 128; 129; 130]. The simple method to achieve a notched band is engraving the various slots on the radiating patch such as U-shape and V-shape slots on both radiating patch and ground plane, C-shape, circular and ring type slots have been studied. In [75], the notch function is achieved by attaching a parasitic patch to the bottom layer of the UWB
antenna. Cutting the slits from radiating edges and also modifying the ground structure and by etching the different shaped slots will also shows a band-notch characteristic. Further, by adding parasitic strips and by using resonators to the radiating patch they have realized the band-notch properties [131; 132; 133].

4.4.1 Design of WiMAX (3.2-4.2 GHz) band-notched multilateral disk monopole antenna with U-slot

4.4.1.1 Geometry

The top and side view configuration of band-notched UWB antenna is as shown in Figure 4.32. The antenna comprised of a circular radiating patch and a partial ground plane connected together with a 50Ω microstripline-fed structure. In this design, the antenna has a dimension of $38 \times 50\,\text{mm}^2$ and etched on the commercial low cost glass epoxy dielectric substrate material. The substrate material has thickness of 1.6 mm with a relative dielectric constant of 4.2 and $\tan \delta$ of 0.02 is employed. The excitation is a 50Ω microstripline feed consists of fixed width $W_f = 3.17\,\text{mm}$. The main structure of the antenna is multilateral circular radiator of truncated area $t_1 = 7.5\,\text{mm}$ and $t_2 = 6.37\,\text{mm}$ within the total radius of $r = 10.7\,\text{mm}$ and an optimized dimensions of U-slot which is engraved on the radiating patch. The partially truncated ground plane with the length of $L_g = 20.45\,\text{mm}$ etched on the bottom surface of the dielectric substrate, and the gap between the multilateral circular patch and the ground plane is $g = 0.5\,\text{mm}$ which is selected for desired bandwidth enhancement.

To carry out the band-notched characteristics, a U-shaped slot etched on the multilateral circular radiating element to achieve the notch band for WiMAX (3.2-4.2 GHz). The band-notch feature is mainly affect by the location and the total length of the U-slot. The length of the U-shaped slot ($U_W + 2L_1 + L_2$) is about half wavelength of the notch frequency (3.2-4.2 GHz) is approximately calculated at center frequency of 3.7 GHz. The mathematical calculation of the wavelength in the medium is given by

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}}\,\text{mm}$$  \hspace{1cm} (4.1)

where,

$$\lambda_0 = \frac{c}{f_0}$$

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The $\lambda_g$ and $\lambda_0$ are the guide and free space wavelengths respectively in mm. The $\varepsilon_{\text{eff}}$, $C$ and $f$ are the effective relative permittivity, velocity of light in free space and center frequency of the notch band respectively. After through parametric study the optimal design parameters are given in Table-I. The photograph of the fabricated band-notched UWB antenna with SMA connector at the tip of the microstripline feed is as shown in Figure 4.33.

### 4.4.1.2 Current distributions of the WiMAX (3.2-4.2 GHz) band-notched UWB antenna.

For better understanding the notch-band characteristics of the antenna the surface current distribution is discussed. Figure 4.34 shows a simulated surface current distribution on the radiating element and the ground plane of the proposed antenna observed in its operating band at 2.4, 3.5, 6.1 and 9.8 GHz for the optimum design. As shown in Figure 4.34 (b) which is observed at 3.5 GHz

![Figure 4.32: Top and side view configuration of band-notched UWB antenna](image-url)
Table 4.2: The optimized design parameters of UWB antenna (Unit: mm)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate width (W)</td>
<td>38</td>
</tr>
<tr>
<td>Substrate length (L)</td>
<td>50</td>
</tr>
<tr>
<td>Feed line width ($W_f$)</td>
<td>3.17</td>
</tr>
<tr>
<td>Feed line length ($L_f$)</td>
<td>20.95</td>
</tr>
<tr>
<td>Actual radius of the patch (r)</td>
<td>10.7</td>
</tr>
<tr>
<td>Substrate thickness (h)</td>
<td>1.6</td>
</tr>
<tr>
<td>Length of the ground plane ($L_g$)</td>
<td>20.45</td>
</tr>
<tr>
<td>Gap between the radiating patch and ground plane (g)</td>
<td>0.5</td>
</tr>
<tr>
<td>U-slot width ($U_w$)</td>
<td>2</td>
</tr>
<tr>
<td>U-slot side arms lengths ($L_1$)</td>
<td>20</td>
</tr>
<tr>
<td>U-slot under arm length ($L_2$)</td>
<td>14</td>
</tr>
<tr>
<td>Height of truncated area $t_1$</td>
<td>7.5</td>
</tr>
<tr>
<td>Width of truncated area $t_2$</td>
<td>6.37</td>
</tr>
</tbody>
</table>

Figure 4.33: The photograph of top and bottom view of fabricated band-notched UWB antenna

it is evident that, the current density is mainly distributed on the edges of the U-shaped slot and this strongly shows that the band-notch characteristics. In Figure 4.34 (a), 4.34 (c) and 4.34 (d) which are measured at 2.4, 6.1 and 9.8 GHz respectively the feeble current flow on the U-shaped slot is observed.

4.4.1.3 Parametric analysis of WiMAX (3.2-4.2 GHz) band-notched UWB antenna

The band-notched UWB antenna is simulated and the results are analyzed with the aid of HFSS software. The prototype of the antenna is fabricated and
Figure 4.34: Simulated surface current distribution of band-notched UWB antenna observed at (a) 2.4 GHz, (b) 3.5 GHz, (c) 6.1 GHz and (d) 9.8 GHz

experimentally analyzed with a Rohde & Schwarz (ZVK model 1127.8651) vector network analyzer. The parametric study is carried out to optimize the antenna and gives the more information about the effectiveness of the essential design parameters. The effect of the notch-band operation is discussed in this section by varying the parameters such as $U_W$, $L_1$ and $L_2$ of the U-shaped slot.

4.4.1.3.1 Effect of width $U_W$ of U-shaped slot: Figure 4.35 illustrates the simulated return loss versus frequency curves for different values of $U_W$. From this figure, it is seen that, the antenna gives an impedance bandwidth ($|S_{11}| < -10$ dB) ranging from 2.36 to more than 12 GHz with the exception of a notch-band at WiMAX (3.2-4.2 GHz). It is also observed that, by varying the width $U_W$ of U-slot the center notched frequency is greatly tuned. It is seen that, the notch frequency is decreases from 4.31 to 3.43 GHz by increasing the width of $U_W$ from 0.25 to 2 mm and by keeping the other parameters $L_1 = 7$ mm and $L_2 = 14$ mm fixed. The optimized value of $U_W = 1$ mm is obtained in this design because antennas gives exact notch band operation.
4.4.1.3.2 Effect of lengths \( L_1 \) and \( L_2 \) of U-shaped slot: The variation of return loss versus frequency plot for different values of \( L_1 \) and \( L_2 \) of U-shaped slot is as shown in Figure 4.36 and Figure 4.37 respectively. From these figures it is observed that, the notched frequency is significantly changed by varying the length of \( L_1 \) and \( L_2 \). The center notch frequencies are decreasing from 5-3.54 GHz and 4.44-3.6 GHz by increasing the \( L_1 \) and \( L_1 \) values from 4-8 mm and 11-15 mm respectively. In order to achieve exact notch frequencies for WiMAX, \( L_1 = 7 \) mm and \( L_2 = 14 \) mm is finally chosen.

4.4.1.4 Radiation characteristics of the WiMAX (3.2-4.2 GHz) band-notched UWB antenna

Figure 4.38 illustrates the optimized design of measured and simulated return loss versus frequency plot of the band-notched UWB antenna. From this figure, it can concluded that, the impedance bandwidth covers the frequency range from 2.36 to more than 12 GHz with the magnitude of return loss less than -10 dB except the notch band from 3.2-4.2 GHz which covers the WiMAX band. The simulation and experimental results are compared and they are in good agreement with each other.
Figure 4.36: Simulation return loss versus frequency curves of band-notched UWB antenna for the various values of $L_1$ keeping $L_2 = 14$ mm and $U_W = 1$ mm

Figure 4.37: Simulation return loss versus frequency curves of band-notched UWB antenna for the various values of $L_2$ keeping $L_1 = 7$ mm and $U_W = 0.2$ mm
4.4.1.5 Measured radiation patterns and gain of the WiMAX (3.2-4.2 GHz) band-notched UWB antenna

The far-field $E$-plane and $H$-plane radiation pattern characteristics including co-polarization and cross-polarization of band-notched UWB antenna. The typical normalized radiation patterns measured at the frequencies of 2.54, 4.68, 6.0 and 9.8 GHz respectively and are shown in Figure 4.39. From the radiation pattern plots, it is clear that, the antenna gives nearly omni-directional pattern in $X-Y$ ($E$-plane) plane essential for UWB antennas and a slightly bidirectional pattern in $Y-Z$ ($H$-plane) plane with cross-polarization at respective frequencies. The simulated peak gain with and without U-shaped slot is plotted from 2 to 12 GHz which is shown in Figure 4.40. From this figure, it is observed that over the UWB operating band, the sharp gain is suddenly drops in the vicinity of 3.6 GHz which validates the notch band characteristics of antennas and a stable gain of 2.3 - 4.2 dB is observed for the other band of frequencies.
Figure 4.39: Measured far-field normalized radiation patterns of band-notched UWB antenna measured at (a) 2.54, (b) 4.68, (c) 6.0 and (d) 9.8 GHz
4.4.2 Design of IEEE 802.11a or HIPERLAN/2 (3.4 – 5.11 GHz) band-notched semi-circular slot loaded monopole antenna

4.4.2.1 Geometry

The designed geometry and its configuration of IEEE 802.11a UWB monopole antenna is as shown in Figure 4.41. The overall size of the antenna including bottom ground plane is $35 \times 50 \text{ mm}^2 \ (W_g \times L_g)$, which is printed on commercially available modified glass epoxy dielectric substrate with a relative permittivity $(\varepsilon_r)$ of 4.2, tangential loss $(\tan \delta)$ of 0.02 and thickness $(h)$ of 1.6 mm. On top surface of the dielectric substrate the segmental arch shape radiating patch with a semi-ring slot and bottom side of the surface the partial finite conducting ground plane of length $(T_g) 20.45 \text{ mm}$ is placed. The arch radiating patch is connected to a $50 \Omega$ microstrip line feed of width $(W_f)$ and length $(L_f)$ which is equal to $(T_g + g)$. The microstrip line $L_f$ and $W_f$ is fixed at 20.95 mm and 3.17 mm respectively. The gap ‘$g$’ is maintained as 0.5 mm between radiating patch and the bottom ground plane. The arch shaped radiating element which is modified from the conventional circular radiating patch having actual radius $R$. The $L_1$, $L_2$ and $L_3$ are the truncated top and side lengths. $S_1$ and $S_2$ are
segmental portions of the slot. In order to produce band-notched characteristics, a semi-ring slot is implanted at middle of the radiating patch. In this design, the band-notch function is particularly affected by the location of the slot length $L_s$. The optimized outer diameter ($D$) of the semi-ring slot is $14 \text{ mm}$. The length of the semi-ring slot ($L_s$) is about half wavelength of center frequency of $3.3-5.1 \text{ GHz}$ i.e. at $4.3 \text{ GHz}$. The rejected frequency can be postulated as,

$$f_{\text{rejection}} = \frac{c}{2L_{\text{slot}} \sqrt{\varepsilon_{\text{eff}}}} \text{ mm}$$  \hspace{1cm} (4.2)

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_r + 1}{2}$$

where, $L_{\text{slot}}$ is the length of the slot in mm, $\varepsilon_{\text{eff}}$ is the effective relative dielectric constant and ‘$C$’ is the velocity of light in mm.

![Figure 4.41: Geometry of IEEE 802.11a antenna](image)

The IEEE.802.11a band-notched UWB antenna is simulated and parametric study is carried out by using Ansofit 3D electromagnetic high-frequency structure simu-
lator (HFSS) software package. The optimized design parameters of this antenna are, \( W_g = 38 \text{ mm}, L_g = 50, W_f = 3.17 \text{ mm}, L_f = 20.95 \text{ mm}, R = 10.7 \text{ mm}, h = 1.6 \text{ mm}, g = 0.5 \text{ mm}, W_s = 0.2 \text{ mm}, T_g = 20.45 \text{ mm}, L_s = 21.2 \text{ mm}, D = 14 \text{ mm}, L_1 = 12.46 \text{ mm}, L_2 = 14.86 \text{ mm}, L_3 = 12.46 \text{ mm} \) and \( S_1 = S_2 = 1.94 \text{ mm} \). Figure 4.42 shows the top and bottom view photographs of the fabricated antenna with SMA connector is mounted at the center tip of the microstripline and ground plane.

**Figure 4.42: Photograph of IEEE 802.11a UWB antenna (a) Top view (b) Bottom view**

The prototype of the IEEE 802.11a UWB antenna is fabricated for validating the realistic design which is as shown in Figure 4.41 and experimentally analysed by measuring various parameters with the help of Rohde & Schwarz ZVK model 1127.8651 German make Vector Network Analyser (VNA). The effect of notch-band characteristics is also studied by varying the dimension of one parameter at a time and by keeping the other parameters constant.

### 4.4.2.2 Surface current distributions of IEEE 802.11a antenna

Figure 4.43 (a)-(d) illustrates the simulated current distributions on the surface of the radiating element and on the ground plane at desired frequencies of 2.43, 4.8, 6.29 and 9.22 GHz respectively. As shown in Figure 4.43 (a), (b) and (d) which is evident that, the current density is mainly flows through the microstripline feed and partial current flow is found along the edges of the slot. But, in the case of notched band at 4.8 GHz which is shown in Figure 4.43 (c), the large current distributed around the semi-ring slot edges is observed. This is because the more current reflected back due to mismatching of impedance at that particular frequency and consequently by inserting semi- ring slot on the radiating patch. The notched frequency is obtained at desired frequency which
will enable the interference of IEEE 802.11a or HIPERLAN/2 frequency bands.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.43}
\caption{Surface current distribution of IEEE 802.11a UWB antenna observed at (a) 2.43 GHz, (b) 4.8 GHz, (c) 6.29 GHz and (d) 9.22 GHz}
\end{figure}

4.4.2.3 Parametric analysis of IEEE 802.11a antenna

The parametric analysis is performed with the help of the HFSS simulation software. The obtained parametric study results along with concluding remarks
for each parameter are narrated in the following sections.

4.4.2.3.1 Effect of length \( (L_s) \) of the semi-ring slot: Figure 4.44 presents the simulated return loss versus frequency curves for different values of \( L_s \). From this figure, it is shown that, length of the semi-ring slot \( (L_s) \) is varied from 19.9 mm to 21.9 mm by keeping values of \( W_s \) and \( T_g \) constant at 2 mm and 20.45 mm respectively. By increasing the length of \( L_s \) the notch bandwidth decreases from 5.8 GHz to 5.15 GHz is prior to reached near the magnitude of the return loss of \( |S_{11}| > -5 \) dB. The optimum slot length is found to be at \( L_s = 21.5 \) mm which gives IEEE 802.11a or HIPERLAN/2 notched frequency range.

![Figure 4.44: Simulated return loss versus frequency plots of IEEE 802.11a UWB antenna for the various values of \( L_s \) by keeping \( W_s = 2 \) mm and \( T_g = 20.45 \) mm](image)

4.4.2.3.2 Effect of length \( (W_s) \) of the semi-ring slot: Figure 4.45 illustrates the simulated return loss versus frequency curves for different values of \( W_s \) when \( L_s \) and \( T_g \) are fixed at 21.5 mm and 20.45 mm respectively. As observed that, the central notch frequency is shifted below from 5.2 GHz to 5.12 GHz by increasing the width of \( W_s \). The optimised value of \( W_s \) is found to be 2 mm. From these results, it is evident that, the bandwidth of notched-band may be easily varied by changing the length and width of the semi-ring slot.
4.4.2.3.3 Effect of ground plane length ($T_g$): Figure 4.46 shows the simulated return loss curves for the different values of $T_g$ when $L_s = 21.5$ mm and $W_s = 2$ mm. It can be seen that, the impedance bandwidth is significantly changes by increasing the size of $T_g$ values from 17.45 mm to 20.45 mm. The optimal value of $T_g$ is found be at 20.45 mm for better impedance matching where we get desired notch band frequency range of 3.3-5.1 GHz.

4.4.2.4 Return loss characteristics of IEEE 802.11a antenna

The experimental and simulated return loss versus frequency response of IEEE 802.11a UWB antenna for the optimized dimensions is plotted in Figure 4.47. The plot indicates that, the antenna reveals a dual band characteristics which covers the 2.4 GHz WLAN and ultra-wideband impedance bandwidth having $|S11| < -10$ dB over an operating frequency range of 2.35 to more than 11 GHz except around band-notched frequency of 3.3 – 5.1 GHz. From this figure it is also clear that, there is a qualitative agreement between the measured and simulated results. However, there is a slight difference between the experimental and simulation results at the higher frequency. This is mainly due to influenced by the coupling effect of the 50Ω SMA connector and physical tolerance in relative permittivity.
of dielectric material.

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Figure 4.46: Simulated return loss versus frequency plots IEEE 802.11a UWB antenna for the various values of \( T_g \) and keeping \( L_S = 21.5 \) mm and \( W_S = 2 \) mm.

Figure 4.47: Experimental and simulated return loss versus frequency plot of IEEE 802.11a UWB antenna.
4.4.2.5 Measured radiation patterns and gain of IEEE 802.11a antenna

Figure 4.48(a)–(e) shows the far-field normalized radiation patterns including co-polarization and cross-polarization E-plane (XY-plane) and H-plane (YZ-plane) measured at 2.8, 5.5, 6.6, 7.47 and 9.4 GHz respectively. From these figures, it is seen that, the antenna exhibits an omnidirectional radiation pattern in H-plane (YZ-plane) and quasi-omnidirectional radiation pattern in E-plane (XZ-plane) with minimum (-20 dB) cross-polarization. It is also observed that, the cross-polarized patterns in both planes are increasing at higher frequencies. The peak gain of the antenna with and without semi-ring slot is as shown in Figure 4.49. It is clearly seen that, the gain is instantly decreasing in between the frequency range of 3.4 to 5.1 GHz which realized that the proposed antenna has a perfect rejection at vicinity of 4.2 GHz for IEEE 802a or HIPERLAN/2 interference frequency bands. The range of the antenna gain over operating frequency bands is about 2.94 to 5.65 dB is observed except at the band notched frequency region. The maximum gain of 5.65 dB is observed at 9 GHz and minimum gain of -4.17 dBi is observed at rejected band. All of these show that, the antenna has good band-notched characteristics and effectively minimize the potential interferences between UWB system and the wireless communication systems achieve remarkable in this study.
Figure 4.48: Measured normalized radiation patterns in E-plane (X-Z plane) and H-plane (Y-Z) of IEEE 802.11a UWB antenna at (a) 2.8 GHz, (b) 5.5 GHz, (c) 6.6 GHz, (d) 7.47 GHz and (e) 9.4 GHz
4.4.3 Design of Bluetooth/WLAN (2.4-2.9 GHz) and UWB (3.1-10.6 GHz) with IEEE 802.11a or HIPERLAN/2 (3.4 – 5.11 GHz) band-notched microstripline-fed (BUI) UWB antenna

4.4.3.1 Geometry

The antenna geometry and optimized dimensions of the band-notched BUI-UWB antenna is as shown in Figure 4.50. The entire antenna structure is printed on a low cost glass epoxy dielectric substrate which having permittivity ($\varepsilon_r$) 4.2, loss tangent ($\delta$) 0.02 and thickness of 1.6 mm. The physical size of this antenna is 38 mm $\times$ 50 mm. On the top surface of the dielectric substrate the disk radiating patch of radius (r) 10.7 mm is placed. The antenna is fed by simple 50Ω microstripline. In this design we selected a disk radiating patch because it is acceptable for good omnidirectional radiation in all directions. Bottom of the antenna structure having a partial truncated ground plane of 19 mm $\times$ 20.45 mm is etched. For the better performance of the impedance matching, the gap ($g$) between radiating patch and the ground plane is kept constant at 0.5 mm. In this structure, the single band-notch filtering property in the IEEE 802.11a or
HIPERLAN/2 (3.4 – 5.11 GHz) is achieved by embedding elliptical ring slot of length ($e_l$) and width ($e_w$) at the middle of the radiating patch. Due to creation of elliptical ring slot can easily avoid the frequency band of 3.4 GHz to 5.11 GHz. Thus the proposed antenna can manage for both 2.4-2.9 GHz (Bluetooth/WLAN) and 3.1-10.6 GHz (UWB). By suitably tuning the elliptical ring slot dimensions especially width ($e_w$) values, the single band-notch characteristic around 3.4 – 5.11 GHz (IEEE 802.11a or HIPERLAN/2) is achieved. The photographs of the fabricated antenna are as shown in Figure 4.51. The optimized design parameters of the antenna are as follow:

$$W = 38 \text{ mm}, \quad L = 50 \text{ mm}, \quad e_l = 47.1 \text{ mm}, \quad e_w = 2 \text{ mm}, \quad W_f = 3.17 \text{ mm}, \quad L_f = 20.95 \text{ mm}, \quad L_g = 20.45 \text{ mm}, \quad R = 10.7 \text{ mm} \quad \text{ and } \quad g = 0.5 \text{ mm} \quad \text{ and } \quad h = 1.6 \text{ mm}.$$
4.4.3.2 Parametric Analysis

The BIU-UWB antenna is simulated using EM 3D full-wave Ansoft HFSS. The fabricated antenna is experimentally measured using Rohde & Schwarz ZVK model 1127.8651 German make Vector Network Analyser (VNA). The effect of single notch-band characteristics is also studied by varying elliptical ring slot dimensions in simulation software.

4.4.3.2.1 Effect of width of elliptical slot ($e_w$): Figure 4.52 shows a simulated return loss versus frequency plot for the various values of $e_w$. In this figure, it is observed that the width of elliptical ring slot $e_w$ is varied from 1.4 mm to 2.2 mm by keeping other parameters are constant. The bandwidths of the band-notch frequencies are increased. For the desired band-notch frequency at the vicinity of IEEE 802.11a or HIPERLAN/2 (3.4 – 5.11 GHz) the optimum width of the elliptical ring slot ($e_w$) is found to be 2 mm.

![Figure 4.52: Return loss versus frequency of BIU-UWB antenna for the values of $e_w$.](image)

4.4.3.2.2 Effect of ground plane length ($L_g$): Figure 4.53 depicts the simulated return loss versus frequency plot for the various values of $L_g$ when $e_w=2$ mm and $e_l=47.1$ mm. From this figure it is clear that, the impedance matching is changes and also affects the performance of the band-notch band widths by increasing the $L_g$ from 18.95 mm to 20.95 mm. The optimized value of $L_g$ is found be 20.45 mm.

Figure 4.54 shows the experimental and simulated return loss versus frequency plots of BIU-UWB antenna for the optimized dimensions. In Figure 4.54, the
antenna meet the expectations of the magnitude of the return loss is less than -10 dB (|S11| < -10 dB) covers the desirable 2.4-2.9 GHz (Bluetooth/WLAN) and ultra-wideband band (3.1 – 10.6 GHz) frequency ranges. From this figure it is also clear that, there is a qualitative agreement between the experimental and simulated results.

Figure 4.54: Experimental and simulated return loss versus frequency of BUI-UWB antenna for the optimized dimensions

4.4.3.3 Current distributions

Figure 4.55 shows the magnitude of the surface current densities of BUI-UWB antenna at frequencies 2.4 GHz, 4.2 GHz, 5.67 GHz and 9.49 GHz for the
optimized design parameters. From Figure 4.55 (b), we can observe that, the more density of current is mainly distributed along the edges of the elliptical ring slot which result in notched-band realization. In figures 4.55 (a), 4.55 (b) and 4.55 (d), the less current is distribution is observed on the closed elliptical ring slot.

![Figure 4.55: The magnitude of the current densities on the surface of BUI-UWB antenna observed at (a) 2.4 GHz, (b) 4.2 GHz, (c) 5.67 GHz and (d) 9.49 GHz](image)

4.4.3.4 Measured radiation patterns and gain of BUI-UWB antenna

Figure 4.56 shows the far-field normalized co-polar and cross-polar radiation patterns in E-plane and H-plane of BIU-UWB antenna measured at the frequencies of 2.4 GHz, 5.67 GHz and 9.49 GHz respectively. Form these figures, the nearly omnidirectional radiation patterns in the E-plane and dipole like bidirectional radiation patterns in H-plane are obtained at their respective frequencies. Figure 4.57 gives the realized gains of BUI-UWB antenna with and without elliptical ring slot within its operating frequency. From this figure it is clear that, the slight stable realized gain of the antenna ranges from 3 dB - 7 dB observed over the entire UWB band except at the 3.1 GHz to 5.11 GHz are about -8 dB
at the vicinity of rejection band. Other than the rejected bands, the gains remain good and stable. All these results show that BUI-UWB antenna has good band-notched characteristics and effectively avoid the potential EM interferences within UWB system achieved in this study.

Figure 4.56: Normalized co- and cross-polar radiation patterns in E-plane and H-plane of BUI-UWB antenna measured at (a) 2.4 GHz, (b) 5.67 GHz and (c) 9.49 GHz
4.4.4 Design of microstripline-fed dual notched-band with pair of elliptical split-ring slots monopole (NEM) UWB antenna

4.4.4.1 Geometry of the antenna

The configuration of dual notched-band NEM-UWB antenna is illustrated in Figure 4.58. The antenna design is sketched and fabricated on a low-cost FR-4 substrate having a relative permittivity ($\varepsilon_r$) of 4.4, loss tangent ($\tan \delta$) of 0.02 and a substrate thickness of 1.6 mm. The antenna is composed of a concave arch-shaped radiating patch with a pair of elliptical split-ring slots and a partial finite-size ground plane on a bottom side of the substrate. The concave arch-shaped radiating element is basically a modified geometry of a conventional circular shape with radius $R$ of 7.9 mm. Further, the side edges of the circular radiating patch are truncated which will form the antenna structure. A rectangular notch with a size of $N_l \times N_w = 3.2 \text{ mm} \times 4 \text{ mm}$ is designed on the mid top of the ground plane that 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 radiating patch and microstripline the distance $d=1.15 \text{ mm}$ is maintained. The entire antenna structure is printed within a small size of $26 \times 32 \text{ mm}^2$ substrate which represents a compact size. A simple $50\Omega$ microstrip
line feed with a length $L_f$ of 15.15 mm and $W_f$ of 3.06 mm is selected to excite the radiating patch.

![Configuration of the proposed dual notched-band NEM-UWB antenna](image)

**Figure 4.58:** Configuration of the proposed dual notched-band NEM-UWB antenna

### 4.4.4.2 Dual notched-band operation

A pair of elliptical split-ring slots is designed to achieve separate notched-bands at 3.5 GHz and 5.8 GHz for WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) systems. The key parameter to predict the center frequencies of the notched bands are mainly depends on the corresponding total length of the slots. In this design, the lengths of the elliptical split-ring slots $e_{ll}$ and $e_{l2}$ are can be approximately determined by one wavelength of the rejected frequencies at 3.5 GHz and 5.75 GHz respectively. The wavelengths for the desired notched frequencies at 3.5 and 5.75 GHz are approximately calculated by the empirical formula given by,

$$
\lambda_g = \frac{\lambda_0}{\left(\varepsilon_r + 1\right)} \text{ cm} \tag{4.3}
$$

and

$$
\therefore \lambda_0 = \frac{c}{f}
$$

where, $\lambda_g$ and $\lambda_0$ are the wavelength in the medium and free space respectively in cm. $c$ is the velocity of light and $\varepsilon_r$ is the relative dielectric constant.
The final optimized design parameters of NEM-UWB antenna are, $R = 7.5$ mm, $T_r = 9.2$ mm, $e_1 = 25.91$ mm, $e_2 = 18.36$ mm, $e_w = 0.5$ mm, $g = 1$ mm, $L_f = 15.15$ mm, $W_f = 3.06$ mm, $L_g = 14$ mm, $N_L = 3.2$ mm and $N_w = 4$ mm. The photograph of the top and bottom view of this antenna is given in Figure 4.59.

![Photograph of the manufactured NEM-UWB antenna](image)

**Figure 4.59: Photograph of the manufactured NEM-UWB antenna**

### 4.4.4.3 Measured and simulated VSWR characteristics

The design of dual notched-band NEM-UWB antenna, the simulation of VSWR plots, current distributions, gain and the parametric study is carried out for better understanding the effect of dual notched-band characteristics. The commercial electromagnetic High Frequency Structure simulator (HFSS) is used for this purpose. Measured VSWR curve and radiation pattern results of the NEM-UWB antenna are obtained by Agilent’s PNA (N5230A) Vector Network Analyzer (VNA). Figure 4.60 shows a comparison of measured and simulated VSWR curves of this antenna with slots and the simulation of VSWR curve for the actual UWB antenna without slots. From this figure, it is well known that, the measured result is in good acceptance with the simulated one. The impedance bandwidth of this antenna is lies from 2.96 to more than 18 GHz for VSWR $\leq 2$ covering the entire UWB frequency band with dual notched-bands of 3.2-3.88 GHz and 5.41-5.96 GHz.

### 4.4.4.4 Simulated current distributions

In order to get better radiation mechanism of the notched-band characteristics, the simulated surface current dispersions at 3.5 and 5.75 GHz for NEM-UWB antenna are illustrated in Figure 4.61. It can be observed from the Figure 4.61 (a) that, the surface current densities at 3.5 GHz is mainly accumulated around the edges of the bigger size elliptical split-ring slot whereas the surface currents...
densities at 5.75 GHz is mainly allocated along the edges of the smaller size elliptical split-ring slot which is given in Figure 4.61 (b). Also, from this figures it is well known that, the NEM-UWB antenna shows a dual notched-band feature within the UWB band.

4.4.4.5 Parametric analysis

To optimize the central frequencies of the notched bands the values of ‘el1’ and ‘el2’ are varied through conducting the parametric study with the aid of electromagnetics Ansys High Frequency Structure Simulator (HFSS) tool. The notched bands can be affected by varying the total lengths of the corresponding slots and slot location of the NEM-UWB antenna. Parametric analysis is conducted for further investigation to understand the effect of notched-bands.

4.4.4.5.1 Effect of lengths of the elliptical split-ring slot ‘el1’ and ‘el2’:
Certainly, the notched bands at 3.5 GHz and 5.75 GHz are implemented by inserting a pair of elliptical split-ring slots in the radiating patch. Figure 4.62 shows the simulated VSWR plots of NEM-UWB antenna with different values of total

![Figure 4.60: Comparison of measured and simulation VSWR plots of with and without NEM-UWB antenna](image)
Figure 4.61: Surface current distributions on NEM-UWB antenna observed at (a) 3.5 GHz and (b) 5.75 GHz.

lengths of the elliptical split-ring slot $e_{l1}$ by keeping $e_{l2}$ value as constant. It can be observed that, with the increase of $e_{l1}$ values, the center frequencies of the corresponding notched-band shifts towards the lower frequency side of the band.

Similarly, the effect of simulated VSWR plots for different values of $e_{l2}$ is shown in Figure 4.63. As observed from this figure that, increasing the total length of the elliptical split-ring slot values $e_{l2}$ and by keeping the $e_{l1}$ value is constant, the center frequencies of the corresponding notched-band shifts towards the lower frequency side of band. In addition, it is evident from the results that the lengths of the corresponding slots and by adjusting the one parameter keeping the other parameters constant, only the corresponding notched band
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Figure 4.62: Simulated VSWR plots of NEM-UWB antenna for different values of $e_{\ell_1}$ by keeping $e_{\ell_2}$ constant.

Figure 4.63: Simulated VSWR plots of NEM-UWB antenna for different values of $e_{\ell_2}$ by keeping $e_{\ell_1}$ constant.
changes without disturbing the other notched-band. When the total lengths of the slots are approximately equal to a half wavelength, the optimal notched-band characteristics can be achieved. Hence in this antenna design the optimal values of the elliptical split-ring slots $e_{11}$ and $e_{12}$ are chosen as 25.91 mm and 18.36 mm respectively which approximately determines the center frequencies of the desired notched-bands of WiMAX (3.3-3.7 GHz) and WLAN (5.725-5.825 GHz) frequency bands.

4.4.4.6 Measured radiation patterns and gain

Figure 4.64 (a-c) represents far-field normalized radiation patterns in both E and H-plane of NEM-UWB dual notched-band antenna measured at 3, 4 and 8.35 GHz respectively. From these figures it is observed that, the proposed antenna reveals a bidirectional radiation pattern in the E-plane (Y-Z plane) and an omnidirectional radiation pattern in the H-plane (X-Z plane). The simulated peak gain plot of the NEM-UWB antenna with and without slots is as shown in Figure 4.65. It can notice from this figure that, the two sudden sharp cutback of the antenna gain can be observed in the rejected frequency bands, this is due to loading a pair of slots onto a radiating patch of NEM-UWB antenna. The peak gains observed are from 3.5 to 5.5 dBi for the UWB operating bands and -3.61 dBi and -4.09 dBi for the rejected bands at 3.5 GHz and 5.75 GHz respectively. This result confers that the proposed NEM-UWB antenna has a good dual notched-band characteristics at WiMAX (3.2-3.7GHz) and WLAN (5.725-5.825 GHz) frequency bands which is to be most required characteristics achieved in this design.

4.4.4.7 Time domain analysis

In order to ensure the time-domain performance, the group delay characteristics of the NEM-UWB antenna has been simulated between two identical prototype antenna models in face-to-face orientation with keeping distance 300 mm between them. Figure 4.66 shows a group delay of response of the NEM-UWB antenna. A constant delay is less than 2 ns are observed throughout the UWB operating band except in the notched bands. This phenomenon represents the proposed antenna exhibits a good time-domain characteristics for linear transmission.
Figure 4.64: Normalized radiation patterns in E and H-plane of NEM-UWB antenna measured at (a) 3 GHz, (b) 4 GHz and (c) 8.35 GHz
4.4.5 Design of microstripline-fed controllable quad band-notched CQN - UWB antenna

4.4.5.1 Geometry and design of the proposed antenna

The antenna structure of the proposed quad band-notched CQN - UWB antenna and its parameters are shown in Figure 4.67, comprises a modified structure of radiating patch and partial ground plane on the top and bottom side of the substrate respectively. The antenna which is fed by a simple 50Ω microstrip-
line of length $L_f = 15.15\, \text{mm}$ and width $W_f = 3.06\, \text{mm}$. The top and bottom conducting structures of this antenna is printed on commercially available FR-4 epoxy dielectric material with a relative permittivity ($\varepsilon_r$), loss tangent ($\tan \delta$) and thickness ($h$) of 4.4, 0.02 and 1.6 mm respectively. The antenna structure is mainly adopted from modifying a disk monopole antenna with radius of 7.9 mm which are truncating top and side portions. Under the microstripline feed in the vicinity of radiating patch and on the center of the ground plane a small rectangular notch is created for the betterment of impedance matching provides the wide impedance bandwidth with VSWR $\leq 2$ over the UWB operating band. As illustrated in Figure 4.66, three separate inverted U-shaped slots are embedded to the radiating patch. The band-notched characteristics are achieved at WiMAX (3.2-3.7 GHz), lower IEEE 802.11a WLAN (5.15-5.35 GHz) and upper IEEE 802.11a WLAN (5.725-5.825 GHz) bands. In order to achieve another band-notched characteristics at lower X-band required for satellite communication band (7.1-7.9 GHz) a pair of inverted U-shaped resonator strips are created at besides of the microstripline feed under the radiating patch. Further, in our design concept, the effectiveness of the band-notched characteristics is controlled by varying length of the three inverted U-shaped slots and inverted U-shaped strips. The photographs of the proposed microstripline-fed controllable quad band-notched UWB antenna monopole is as shown in Figure 4.68. The optimized dimensions for design antenna parameters are follows: $W_f = 3.06\, \text{mm}$, $L_f = 15.15\, \text{mm}$, $T_1$ & $T_2 = 9.23\, \text{mm}$, $T_3 = 12\, \text{mm}$, Slot a $(2(S_{a1})+S_{a2}) = 26\, \text{mm}$, Slot b $(2(S_{b1})+S_{b2}) = 16.5\, \text{mm}$, Slot c $(2(S_{c1})+2(S_{c2})+S_{c3}) = 20.4\, \text{mm}$, $W = 0.4\, \text{mm}$, $l_1 = 5.1\, \text{mm}$, $l_2 = 2\, \text{mm}$, $W_s = 0.3\, \text{mm}$, $L_g = 14\, \text{mm}$, $g = 1.15\, \text{mm}$, $N_l = 3.2$ and $N_w = 4\, \text{mm}$.

4.4.5.2 Realization of the quad band-notched characteristics with individual band rejection elements

To easily understand the realization of the compact UWB monopole antenna with quad band-notched characteristics, the individual evolutionary prototypes of the compact UWB monopole antennas with realization of individual band-notched component have been discussed. The design of evolution process of the microstripline-fed controllable quad band-notched UWB monopole antennas is illustrated in Figure 4.69. For the compactness purpose the parameters of the evolutionary design antennas (Antenna-1, Antenna-2, Antenna-3 and Antenna-4) are maintained as same as that of the CQN-UWB monopole antenna (Proposed
antenna) with individual single band-notched at 3.6 GHz, 5.25 GHz, 5.75 GHz and 7.45 GHz. Individual band-notched property is achieved with UWB antenna by embedding U-shaped inverted slots (slot a, slot b and slot c) and inverted U-shaped strips respectively. Firstly, as shown in the Figure 4.69, the truncated planar microstripline-fed disk monopole antenna which is designated as Antenna-I in this case, is developed to cover the UWB frequency band of 3.1 – 10 GHz. Then,
each of four UWB antennas has been designed with individual band-notched characteristics to realize the multiple band-rejection UWB antennas. Figure 4.70 shows the simulated VSWR characteristics of the UWB antennas with single band-notched function. Four rejected bands for VSWR $\leq 2$ are observed at the vicinity of narrow frequency bands of 3.3–3.82 GHz, 4.8–5.36 GHz, 5.7–6.2 GHz, 7.1–8.1 through antennas Antenna-2 to Antenna-5 respectively.

![Figure 4.69: Design evolution of the CQN-UWB antenna](image)

The band-notched function at 3.6 GHz is mainly created due to the inserting bigger inverted U-shaped slot (slot a) at the edges of the radiating patch and optimum length and width are chosen as slot a $(2(S_{a1})+S_{a2}) = 26$ mm and $W=0.4$ respectively. Another band-notched characteristic at 5.75 GHz is produced due the creation of the inverted U-shaped slot (slot b) at the middle of the radiating patch and optimum parameter dimensions of the slot-b chosen as Slot $b = (2(S_{b1})+S_{b2}) = 16.5$ mm. Again, the third band-notched characteristics near 5.25 GHz is achieved by etching the closed inverted U-shaped slot (slot c) at the lower side of the radiating patch with optimum dimensions chosen as Slot $c =$
(2S_{c1} + 2S_{c2}) + S_{c3} = 20.4 \text{ mm}, \ W = 0.4 \text{ mm} \text{ respectively. Further, by introducing inverted U-shaped strips which will act as a filter resonator placed adjacent to the microstripline feed, exact at under the radiating patch, the band-notched property is observed at 7.45 \text{ GHz} with an optimum dimensions of l_1 = 5.1 \text{ mm}, l_2 = 2 \text{ mm}, W_s = 0.3 \text{ mm}. Each band-notched element is considered and finely tuned independently without affecting the other notched bands. Hence, the impedance matching is only affected through each of four band-notched functions only.

Figure 4.70: Simulated VSWR plots of the various antenna structures shown in Figure 4.69

4.4.5.3 Measured and simulated VSWR characteristics

The successfully manufactured antenna and their parameters are measured using a Rohde & Schwarz ZVK model 1127.8651 German make Vector Network Analyzer (VNA). Figure 4.71 shows a comparison of measured and simulated VSWRs of the CQN-UWB antenna. From this figure, it is seen that, the measured VWSR is in good agreement with the simulated one. The impedance bandwidth of CQN-UWB antenna is covering from 3.1 to more than 18 \text{ GHz} for VSWR \leq 2 the entire UWB (3.1-10.6 \text{ GHz}) operating band with quad control-
lable notched-bands of 3.6, 5.25, 5.75 and 7.45 GHz which rejects the interference of WiMAX (3.2-3.88 GHz), WLAN (5.15-5.35 GHZ), WLAN (5.725-5.825 GHz) and X-band satellite communication system (7.25-7.75 GHz) respectively over the UWB operating band.

Figure 4.71: Variation of VSWR versus frequency plots for CQN-UWB monopole antenna

Figure 4.72 shows the simulated impedance (both real and imaginary parts) plot of the CQN-UWB monopole antenna. From this figure it is clear that, the impedance mismatched at notched frequency bands around 3.6, 5.25, 5.75 and 7.2 GHz, respectively.

4.4.5.4 Current distributions and 3D radiation patterns of triple band-notched truncated CDUMA

The simulated surface current distributions in magnitude form are observed at 3.6, 5.25, 5.75 and 7.45 GHz for the CQN-UWB antenna which is illustrated in Figure 5.73. It can be observed from Figure 5.73 (a) (b) and (c) that, the larger current distributing along the edges of the inverted U-shaped band-notched elements (slot a, slot b and slot c) and the microstripline feed is effective figure.
Figure 4.72: Simulated impedance plot of the CQN-UWB monopole antenna

From the Figure 4.73 (d), it is clear that, with the use of inverted U-shaped strip resonators to the radiating patch, the more current distributions are concentrated strongly around the inverted U-shaped resonator another notched frequency of 7.45 GHz is observed. Hence, the CQN-UWB antenna shows a quad notched-band feature at WiMAX (3.2-3.88 GHz), WLAN (5.15-5.35 GHZ), WLAN (5.725-5.825 GHz) and X-band satellite communication system (7.25-7.75 GHz) within the UWB band.

4.4.5.5 Measured radiation patterns and gain of the triple band-notched truncated CDUMA

The far-field normalized radiation patterns measured at 3.27, 3.86, 5.50 and 8.95 GHz are depicted in Figure 4.74. As noticed in figure, nearly omnidirectional patterns in the H-plane and bidirectional patterns in the E-plane are obtained. However, at the frequency of 5.5, 8.95 GHz, the radiation patterns illustrated in the H-plane are slightly less bidirectional because of the higher-order resonant modes at these frequencies.

The simulated gain of the CQN-UWB antenna is shown in Figure 4.75. From this figure it is noticed that, four sharp decrease of antenna gain can be observed at notched frequency bands of 3.6, 5.25, 5.75 and 7.2 GHz respectively. Further,
the average gains are from 4.6 dBi to 7.8 dBi for the UWB operating band is observed. The decreased gains are -5.9 dBi, -3.5, -5.4 and -5.5 dBi observed for the rejected bands. Hence, the presented results of the CQN-UWB antenna has good dual quad-notched characteristics at the WiMAX (3.2-3.88 GHz), WLAN (5.15-5.35 GHZ), WLAN (5.725-5.825 GHz) and X-band satellite communication system (7.25-7.75 GHz) without changing its UWB nature and omni-directional patterns.
Figure 4.74: Normalized radiation patterns in E and H-plane of CQN-UWB antenna measured at (a) 3.27 GHz, (b) 3.86 GHz, (c) 5.50 GHz and (d) 8.95 GHz
4.5 Design considerations of planar disk microstripline-fed UWB monopole antenna (PDMUMA)

Studies in the previous sections have indicated that the ultra-wideband of the various PDMUMA and various truncated PDMUMA with multiple band-notched characteristics are investigated by the combination of 50Ω microstripline-fed, circular disk radiator and the partially truncated ground plane. For the design point of view, the 50Ω transmission-line model has been selected because it gives good physical insight for the design of conventional PDMUMA. The proposed PDMUMA are designed by using direct microstripline feed technique. In direct feed, the feeding point is on one edge of the patch as shown in Figure 4.1. The quarter wave length transformer compensates the impedance differences between the patch and the 50Ω feed line. The radius of the circular disk monopole antenna is calculated according to formulas found in [1].

1. Disk radiating patch design parameters: For the circular patch there is only one degree of freedom to control i.e. is radius of the patch. A design procedure is outlined which leads to practical designs of PDMUMA. The
procedure assumes that, the specified information includes the dielectric constant of substrate ($\varepsilon_r$), the frequency ($f_r$) and the height of the substrate $h$. The procedure is as follows,

- **Determination the actual radius of the disk radiating patch:**
  The actual radius of circular patch, is given by,

  \[
a = \frac{F}{\left\{1 + \frac{2h}{\pi \varepsilon_r F} \left[\ln \left(\frac{\pi F}{2h}\right) + 1.7726\right]\right\}^2} \text{ mm} \quad (4.4)
  \]

  where,

  \[F = \frac{8.791 \times 10^9}{f_r \sqrt{\varepsilon_r}}\]

  For the circular patch a correction is introduced by using an effective radius $a_e$, to replace the actual radius $a$, given by,

  \[
a_e = a \left\{1 + \frac{2h}{\pi a \varepsilon_r} \left[\ln \left(\frac{\pi a}{2h}\right) + 1.7726\right]\right\}^{\frac{1}{2}} \text{ mm} \quad (4.5)
  \]

2. **Design of microstrip line feed:** The microstrip line feed is designed by using the $W/d$ ratio equation taking the known value of characteristic impedance $Z_0$ and dielectric constant of substrate material $\varepsilon_r$ and the design equations are, For a given characteristics impedance $Z_0$ and dielectric constant $\varepsilon_r$, the $W/d$ ratio can be found as:

  \[
  W/d = \left[\frac{C}{2f_r(\varepsilon_e)^{\frac{1}{2}}}\right] \text{ for } W/d < 2
  \]

  and

  \[
  W/d = \frac{2}{\pi} \left[\frac{B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r} \left\{\ln(2B - 1) + 0.39 - \frac{0.61}{\varepsilon_r}\right\}}{\ln(2B - 1)} + 0.39 - \frac{0.61}{\varepsilon_r}\right] \text{ for } W/d > 2
  \]

  where,

  \[A = \frac{Z_0}{60} \sqrt{\frac{\varepsilon_r + 1}{2}} + \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \left(0.23 + \frac{0.11}{\varepsilon_r}\right)\]

  and

  \[B = \frac{377\pi}{2Z_0 \sqrt{\varepsilon_r}}\]
Hence effective dielectric constant and width of microstrip line calculated by the above equation and guided wave length of microstrip line calculated by:

\[ \lambda_g = \left[ \frac{\lambda_0}{\sqrt{\varepsilon_{eff}}} \right] \text{mm} \quad (4.8) \]

where,

\[ \varepsilon_{eff} = \varepsilon_r - \left[ \frac{\varepsilon_r - \varepsilon_e}{1 + G \left( \frac{L}{f_p} \right)^2} \right] \quad (4.9) \]

\[ G = \left( \frac{Z_0 - \frac{5}{60}}{2 \mu_0 h} \right)^{\frac{1}{2}} + 0.004Z_0 \quad (4.10) \]

\[ f_p = \frac{Z_0}{2 \mu_0 h} \text{ Hz} \quad (4.11) \]

\[ \mu_0 = 4 \pi \times 10^{-9} \quad (4.12) \]

\[ \lambda_0 = \frac{C}{f_r} \quad (4.13) \]

The length of microstripline \( L_f \) is taken as \( \lambda_g/2 \) in this study in order to keep minimum loss in microstripline feed. If feed line is connected along the edge of PDMUMA. It is necessary to find the 50\( \Omega \) impedance point along the edge of PDMUMA. The equation is used to calculate the 50\( \Omega \) impedance point is given by,

\[ R_{in} = \left( \frac{120 \lambda_0}{240(2a)\lambda_0(1 + \tan^2 \beta l)} \right) \left( \frac{\tan^2 \beta l + \tan^4 \beta l}{1 + \tan^2 \beta l} \right) \quad \Omega \quad (4.14) \]

where,

\[ \beta = \frac{2\pi \sqrt{\varepsilon_r}}{\lambda_0} \quad (4.15) \]

and

\[ l = \frac{\theta \pi}{180\beta} \]

Hence by using the above equations, the microstripline feed point \( W_f \) is identified and microstripline can be connected at along the edge of PDMUMA. After calculating \( R_{in} \) at the edge of the PDMUMA, the microstrip line may be connected directly to this point. Similarly, the same procedure can be used for the design and development of CPW-fed disk UWB monopole an-
tennas which will be discussed in the next chapter.

The Experimental and simulation investigations of the various CPW-fed disk UWB monopole antennas and their parametric analysis are reported in chapter 5.