

Chapter – 2

Literature Review

2.1 Introduction

FCC introduced the unlicensed ultra wideband (UWB) from 3.1GHz-10.6GHz with fractional bandwidth of 109.48% for commercial communication applications [1]. Due to this, the need for applications for UWB devices rolled out which is bifurcated into three types namely (a) Imaging systems (including GPRs) (b) Radar system in vehicles and (c) Measurement and communication systems. However, GPS system working at 2.575GHz, Bluetooth at 2.4GHz is the other existing wireless applications and to avoid these interferences, the lower UWB bandwidth was fixed at 3.1GHz and higher frequency at 10.6GHz with low emission of -42.3dBm/MHz (75nanowatts/MHz). Moreover, other existing wireless communication such as WiMAX along with C-band, WLAN and X-band downlink satellite communication system with bandwidth of 3.3GHz-3.8GHz, 3.8GHz-4.2GHz, 5.15GHz-5.825GHz and 7.25GHz-7.75GHz respectively will interfere with FCC-UWB bandwidth. The above said interfering bands are eliminated by using different techniques such as slots on radiator, Electromagnetic Coupling technique (ECT) or by Complimentary split ring resonator (CSRR). A detail literature review study is carried out to study UWB antennas with notched function, Antennas on Si Substrate and Phase shifters.

2.2 Monopole UWB Antenna with Microstrip Feed

The simple microstrip patch antennas have narrow bandwidth. To enhance the bandwidth from narrow to wide, two techniques have been developed. One by impedance matching technique and other by introducing multiple resonances, wider bandwidth to cover UWB bandwidth. Wide impedance matching is achieved by introducing quarter wavelength transformer or tuning stubs. UWB antennas features such as wide frequency Impedance bandwidth, simple structure, ease of fabrication on printed circuit boards (PCB) and omni-directional radiation patterns in the entire band, makes it a justifying applicant for UWB applications in wireless communication. UWB antennas with various radiating shape along with modified ground plane to cover UWB bandwidth is carried out [2]-[83].
One side of the Microwave substrate in planar antennas consists of radiating patch which is fed by 50Ω microstrip line with ground plane on opposite side while in Coplanar waveguide (CPW) feed microstrip antenna, both radiating patch with microstrip and ground plane are printed on the same plane. Figure 2.1 (2.11-2.79) shows different shape UWB
antenna configuration covering FCC specified impedance bandwidth (3.1GHz-10.6GHz) with fractional impedance bandwidth of 109.48%. The radiating patch can be of square, rectangle, triangle, circular, annular ring, elliptical (horizontal and vertical), pentagon or hexagon as shown in Figure 2.1(2.11-2.19) and the simulated results show that the UWB antennas maintain a wide bandwidth (3.08GHz-12.69GHz) and with an average gain of nearly 2.58dBi maintaining good radiation properties and are applicable to UWB body centric UWB wireless networks [2]. To design above said UWB antennas different substrate like FR4, RT Duroid5870, RT Duroid5880, Silicon etc. with dielectric constants of 4.4, 2.3, 2.2, and 11.9 respectively are used. The centre frequency (\(f_c\)) for design of UWB antenna is considered. Moreover, by considering guide wavelength (\(\lambda_g\) in GHz), the dimensions of the radiating patch is calculated by \(\lambda_g=\frac{k}{f_c\sqrt{\varepsilon_r}}\), where \(k\) is the velocity of light in free space (\(3\times10^8\)m/s). For antenna, the return loss impedance bandwidth should be less than -10dB or should maintain a VSWR ratio 2:1 in the entire operating band. Planar octagonal-shaped radiating patch is modified by etching minimal distribution area of current on the metal surface of radiating patch with a fractional bandwidth of 151% (2.50GHz - 18GHz), so that RCS (Reduced Radar Cross Section) is reduced up to 25dBsm making it capable for stealth platform radar applications [3]. For multi-service applications together with Wi-Fi (2.4GHz), Bluetooth (v1.0-v4.0), WiMAX (2.5GHz / 5.5GHz) Bluetooth (4.0) or wireless UWB (3.10GHz - 10.6GHz) and has also suitable frequency response for close range radar and satellite communication in the X-band (8.0GHz - 12GHz) and Ku band (12GHz-18GHz) applications, a conical monopole antenna for UWB and multi-service applications is presented in [4]. Fork-shaped radiating patch with rectangular ground plane provides dual-band operations as shown in Figure 2.1(2.21) covering 2.400GHz - 2.484GHz (Bluetooth) and 3.10GHz - 10.6GHz (UWB) frequency bands [5]. Planar Quadra-shape radiating patch with dual rectangular slots and a ground plane with overturned T-shaped notch as represented by Figure 2.1(2.22) provides improved -10dB return loss with preserving good radiation pattern in the entire band [6]. By modifying the conventional rectangular patch antenna with two circled concave or convex profiles as shown in Figure 2.1(2.23) and Figure 2.1(2.24) resulting in UWB antenna with impedance bandwidth of 3.80GHz-13.8GHz [7]. Moreover, by adding stairs and stubs with slotted fractional ground plane is optimized to obtain UWB antenna
represented by Figure 2.1(2.26) [8]. From [9], a rectangular patch monopole antenna with microstrip feed with compact and miniaturized tapered U slot on it with truncated ground plane is designed for wireless applications with antenna dimension of 28.8×32.4mm² on FR4 substrate with relative permittivity \( \varepsilon_r = 4.40 \) and substrate thickness 1.60mm. An elliptical shape radiating patch antenna is reported in [10] which features two types of conductive polymers, PEDOT and PPy (polypyrrole) with different thickness and conductivities resulting in high efficiency in the UWB band. A Ultra wide-band antenna etched on low cost FR4 epoxy microwave substrate consist of radiating patch with parachute-like structure and overturned U-shaped incision on the ground plane with size of 20×30×1mm³ results in broader impedance bandwidth coverage from 2.75GHz to 20.0GHz for \( S_{11} \leq -10\)dB [11]. An incorporation of the tele-communication system surrounded by garment and wearable merchandise known as fabric antenna is reported in [12]. A simple circular patch with T-slot arrangement and a fractional ground plane antenna is also developed as shown in Figure 2.1 (2.30). Measurement of reflection coefficient was also carried out at different curve angles of 20°, 30°, 40°, 50°, 60°, 70°, and 80° for embroidered performance of antenna in wet conditions was also investigated for four states : (i) inside water (ii) antenna immediately wet (iii) antenna approximately dry and (iv) antenna immediately dry for both conductive and nonconductive materials. As reported in [13], antenna with dimension of 40mm×38mm consisting of regular dodecagon of each side measuring 5.17mm as shown in Figure 2.1(2.31) is printed on one side of FR4 substrate with thickness 1.6mm along with rectangular ground plane dimension of length 20mm and width 5mm on other side of substrate for revealing breast tumor in the vicinity of UWB range. Care has also been taken by confining Specific Absorption Rate (SAR) within admissible range surrounding tissues and skin. By joining two distinct semi ellipses through their major axes and triangular-shape groove at ground plane as shown in Figure 2.1(2.32), antenna for the application on Bluetooth and UWB is fabricated and the designed exhibits good omni directional pattern in H-plane and dipole-like pattern in E-plane at 2.45GHz and 3.10GHz. At higher frequencies, the cross-polarization in both E-plane and H-plane increases due to increase in area of radiation [14]. By embedding elliptical patch with a trapezoid as represented by Figure 2.1(2.33), wide slot UWB antenna with compact dimension of 30×30mm² is designed. Furthermore, the microstrip line is tapered for
impedance matching and hexagonal slot is etched from a finite ground plane placed on
other of microwave substrate resulting in fractional impedance bandwidth of 145%
(2.90GHz-18.00GHz) and thus wide-slot antenna for UWB application is obtained [15].
FR4 microwave substrate with size 30mm×30mm×1mm is used to design ultra wide-band
antenna by etching elliptical shape radiating patch which also includes three low frequency
range communication system which is shown in Figure 2.1(2.35). The above said low
frequency communication are obtained by folded CLRRs (Capacitive Load Line
Resonators) which leads to lower communication bands including GSM (Global system for
Mobile Communication) with center frequency of 1.780GHz, WCDMA (Wideband code
division multiple access) with center frequency 2.150GHz and WLAN (Wireless local area
network) with center frequency 2.4GHz. It is worth noting that all the three lower bands are
designed at quarter wavelength with respect to their center frequency [17]. Dipole like
radiation pattern in E-plane and omni-directional pattern is obtained in H-plane with dome-
topped bowl-shaped radiating patch as shown in Figure 2.1(2.38). Radiation pattern are
measured for wide bandwidth at 3.40GHz, 8.00GHz as reported in [20]. An M-shaped
radiating patch replacing conventional monopole patch antenna with modified cutting
rectangular slots in ground plane and Beak-shape radiating with two rectangular slots on
the radiator along with hexagonal-shape defected ground structure (DGS) is reported in
[22] and [23] respectively which are shown in Figure 2.1(2.40) and Figure 2.1(2.41)
respectively for UWB applications. In [24], a UWB antenna with dimension of
32mm×70mm printed on Taconic TLC-30 substrate is reported for MIMO ultra wide-band
antenna applications. Another Multiple Input Multiple Output ultra wide-band antenna is
reported in [25]. As shown in Figure 2.1(2.43) and Figure 2.1(2.44), dual monopoles are
located side-to-side at a spacing 4mm with subsequent radiator placed at 90° with distance
1mm to prevent mutual coupling. Diversity performance was calculated by envelope
correlation coefficient resulting below -20dB. A worldwide method for fabricating ultra
wide-band variety antenna is proposed in [27]. By using this methodology of familiar
symmetrical UWB antenna as shown in Figure 2.1(2.46), the distance between the dual
radiators and feeding lines are nearly equal which results in a complicated structure to
minimize mutual decoupling between dual radiators, a diversified circular disc ultra wide-
band monopole antenna is designed. For the bandwidth improvement, DGS (defected
ground plane) is implemented in ground plane along with elliptical radiator including eleven step slots forming monopole antenna as shown in Figure 2.1(2.52) for diversified applications in ultra wide-band range [30].

2.3 UWB Antenna with Extended Bandwidth, Electromagnetic Coupling and CPW Feed Antenna
Figure 2.2: UWB Monopole Planar and CPW Antennas with enhanced bandwidth.

Figure 2.2 shows different monopole antennas with Electromagnetic coupling, Fractal (Planar and CPW feed), CPW feed antennas, extended bandwidth and multi-band antennas are published in [31]-[83]. By using different parasitic elements in the conductor-backed plane, higher resonant frequencies are excited which are discussed below [31]-[36]. As discussed in [31], impedance bandwidth of the antenna is increased by introduction of couple inverted U-shaped slots in the ground plane. But these results only increase of frequency bandwidth in the higher range side and there is deficiency of radiation in the lower side. However, to overcome this problem a pair of L-shaped elements as shown in Figure 2.2(2.10) which acts as resonator leading to coupling of current from ground structure to the parasitic element. This modification leads to improvement of bandwidth and two new resonance frequencies at 11.00GHz and 14.10GHz are excited. As reported in [32], a quadrangle radiating patch with an flipped T-shaped slot and a ground plane with an flipped T-shaped conductor above the ground plane as shown in Figure 2.2(2.11) leads to a wider usable bandwidth of more than 130% (2.91GHz-14.1GHz). Higher frequency resonance is also excited leading to new higher frequency resonance of 18.37GHz. This is due to etching of dual L-type slot in the ground plane and insertion of pair of L-type conductor above the ground plane in air gap distance as shown in Figure 2.2(2.12). Planar radiating patch along with 50Ω microstrip feed with fractal design as mentioned in [37]-[42], also provides UWB band coverage. The radiating element [37] consists of three stage Sierpinski fractal geometry. In fractal radiating concept, generator and initiator come into play where Minkowski type fractal which acts as generator is obtained by sequenced iterations and in turn is applied to octagonal geometry which acts as initiator [38]. For
design of UWB antenna various type of fractal geometry such as Koch Snowflake, Hexagonal shape, Sierpinski Triangle and irregular geometries has been reported. This concept has the advantage of reduction of size of the antenna without affecting the performance of the antenna. Fractal geometry has the property of space filing which in turn results in increase of effective electrical path length of the antenna in a given small area. As discussed in [39] for UWB application, miniature quasi self-complimentary antenna with crossbar fractal boundary is reported. Furthermore, to attain wideband characteristics hexagonal shape fractal patch and customized ground plane are used [42]. A variety of types of ultra wide-band microstrip antenna with Coplanar Waveguide (CPW) feed are reported in [43]-[61]. U-type square shape radiating element which is formed by combining dual parasitic tuning stubs is fed by coplanar wave-guide as shown in Figure 2.2(1.17) to obtain ultra wide-band characteristics [43]. Transmitting of short pulses over a short range results in distortion less impedance bandwidth. As reported in [45], UWB characteristics are also obtained by dual non centric circular slots fed by coplanar wave-guide feed on the same plane of the radiating surface as represented by Figure 2.2(1.19). To obtain dual-band application monopole antenna in UWB range with PCS (Personal Communication System) and WLAN (Wireless Local Area Network), trident type radiating patch as shown in Figure 2.2(2.21) is fed by coplanar wave-guide feed is reported in [47]. By loading inverted L-strip over the conventional monopole square patch antenna and by vertically extending the ground towards two sides as shown in Figure 2.2(2.23) is used to minimize the monopole radiating patch. Also, to increase the bandwidth, four rectangular slots are etched in the rectangular patch to enhance the bandwidth which is reported in [54]. CPW-fed fractal UWB antennas are reported in [56]-[61]. In the age of modern wireless communication system, antenna with capability of operating in multiple band operation is designed with coplanar wave-guide feed antenna with inscribed circle square shaped fractal antenna with good impedance bandwidth and radiation pattern [56]. In coplanar wave-guide feed UWB monopole antenna where multi-resonance technique is applied is reported in [57]. At the corners of polygon patch with addition of small fractal elements, ultra wide-band antenna characteristics are obtained. Fractal antenna with CPW-feed is reported in [59] which cover 147.83% impedance bandwidth at VSWR 2:1. A new triangular wheel shape (TWS) CPW-feed fractal antenna and CPW nanoarm fractal antenna are reported in [60]-[61] for ultra
wide-band applications. To enhance the impedance bandwidth, modification either in the
ground plane or radiating patch has been reported in [62]-[64]. As shown in Figure
2.2(2.38), introduction of inverted L-shaped parasitic structures, high frequency is
resonated at 13.7GHz [62] as shown in Figure 2.2(2.38). In Figure 2.39, the radiating patch
is modified by T-shaped slots which is responsible for bandwidth enhancement from
10.30GHz-16.2GHz and also by embedding dual L-shaped sleeves in the ground plane,
improvement of VSWR characteristics below 2 is observed [63]. To achieve additional
resonances at lower and higher frequency at 2.90GHz and 10.70GHz respectively [64],
horizontal H-shape slot is etched in the ground plane as shown in Figure 2.2(2.40).
Moreover, to extend the bandwidth further as represented by Figure 2.2(2.41), vertically
placed H-shape element is etched which resonates at 14.70GHz and 17.00GHz respectively,
thereby increasing the overall impedance bandwidth. Figure 2.2(2.42) shows multi
resonance antenna with ordinary square monopole radiating patch covering UWB
bandwidth from 3.40GHz-10.6GHz. By etching single pair of U-type slots in the ground
plane extra upper tone is excited at 11.0GHz and by introduction of two pair of U-shaped
slots higher resonance 14.0GHz is excited. Removing two rectangular slots in the ground
plane as shown in Figure 2.2(2.44), based on ECT: modified V-shaped protruded strip,
etching dual of E-shaped slots in the ground plane or etched pair of rectangular-ring slits in
the customized ground plane and by inserting dual rectangular shaped slots in the ground
plane which are shown by Figure 2.2(2.43)-(2.45) and Figure 2.2(2.47)-(2.48), bandwidth
enhancement is achieved at higher resonance frequency. Different shape radiating patch
antennas other than conventional radiators such as rectangular, circular, triangular, are
reported in [65]-[74]. Higher order mode excitation as shown in Figure 2.2(2.51) where
different modes TM10-TM70 are excited for high gain is achieved [75]. Antenna with
Multiband characteristics for cellular phone as shown in Figure 2.2(2.52) is obtained by
inserting branch lines and a shorted parasitic patch which also results in wide operating
band [76]. As shown in Figure 2.2(2.53)-(2.54), represent Penta-band and Hexa-band
antenna respectively which are applicable for wireless applications including Bluetooth
(2.43GHz-2.54GHz), WiMAX band (3.71GHz-3.77GHz), WLAN (4.99GHz-5.13GHz),
Upper WLAN (6.29GHz-6.43GHz), C band (7.32GHz-7.50GHz) and WLAN band
(2.56GHz-2.63GHz, 2.94GHz-3.05GHz), WiMAX band (3.34GHz-3.55GHz, 4.81GHz-4.92GHz), WLAN band (5.27GHz-5.34GHz) with upper WLAN of 6.88GHz [77].

2.4 Antenna Characterization of Microstrip Line Feed UWB Antenna

In order to study the complete characteristics of above discussed Microstrip feed UWB antennas which are shown in Figure 2.1(2.10-2.79) and Figure 2.2(2.10-2.55), antenna characterization in both frequency domain and time domain is carried out. To carry out the above said characterization, one of the antennas is considered as shown in Figure 2.2(2.42). Frequency domain characterization includes VSWR or return loss study, Current density distribution characteristics, Gain Vs Frequency characteristics, Input Impedance, Radiation Efficiency (%) and Radiation Pattern in both E plane (yz-plane) and H Plane (xz-plane) with co-polarization and cross-polarization, whereas time domain characterization includes fidelity factor, impulse response and group delay.

2.4.1 Frequency domain characterization

![Diagram of UWB monopole antenna](image)

**Figure 2.3:** UWB monopole antenna with extended bandwidth (a) Front view (b) Ground view.
In order to carry out frequency domain characterization, a UWB antenna is simulated by commercially available Ansys EM High Frequency Structural Simulator (HFSS). The width ($W_{\text{sub}}$) of the patch is calculated by

$$W_{\text{patch}} = \frac{k}{2} \times f_0 \sqrt{\left(\varepsilon_r + 1\right)/2}$$

(2.1)

where $f_0$ is the operating Frequency (GHz), $k$ is velocity of light ($3 \times 10^8$ m/s), $\varepsilon_r$ is the dielectric constant of the microwave-substrate. Length ($L_{\text{patch}}$) of the patch is given by

$$L_{\text{patch}} = L_{\text{eff}} - (2 \times \Delta L)$$

(2.2)

where $L_{\text{eff}}$ is the effective length and $\Delta L$ is the incremental length which are represented by

$$\varepsilon_{\text{reff}} = \frac{1}{2} \left( \varepsilon_r + 1 + \frac{12}{1 + \frac{h_{\text{sub}}}{W_f}} \right)^{-0.5}$$

(2.3)

$$\Delta L = 0.412 \ h_{\text{sub}} \ \frac{(\varepsilon_{\text{reff}} + 0.3) (W_{\text{sub}}/h_{\text{sub}} + 0.262)}{(\varepsilon_{\text{reff}} - 0.258) (W_{\text{sub}}/h_{\text{sub}} + 0.813)}$$

(2.4)

where $W_f$ is the width of the $50 \Omega$ microstrip feed line and $h_{\text{sub}}$ is the height of the substrate. Figure 2.3 shows UWB antenna configuration printed on microwave-FR4 substrate with permittivity 4.40 and loss tangent 0.0180. Dimension of antenna is $W_{\text{sub}} \times L_{\text{sub}} \times h_{\text{sub}} =$
12×18×1.6 mm³. VSWR curve for ordinary rectangular monopole antenna without and with rectangular ring slits in the ground plane is shown in Figure 2.4. Antenna configuration excluding rectangular slits from the ground plane results in fractional bandwidth coverage from 3.30GHz-10.70GHz. Moreover, by etched rectangular slits in the ground plane (Defected ground structure) leads to extra current path. This results in change of the circuit elements values (inductance/capacitance) paths which lead to wider impedance bandwidth.

![Figure 2.5](image.png)

**Figure 2.5:** Current density distributions at (a) 6.85GHz (b) 14GHz.

Simulated current density distribution for the antenna shown in Figure 2.3 is carried out at center design frequency of 6.85GHz and higher excited resonance at 10GHz. As illustrated in Figure 2.5(a), current density distribution is uniform for radiating patch at 6.85GHz whereas for higher frequency at 14GHz as illustrated in Figure 2.5(b), current density is concentrated more on the edges of the inner and outer of the four U-type slits in the ground plane.

### 2.4.2 Time domain characterization

Representation of the antenna analysis in Figure 2.6 reveals that received pulses in dual orientation (Side-to-Side and Face-to-Face) have good identical comparison between received and transmitted pulses. **Equation 2.5** represents calculation of Fidelity Factor (F) where a(t) and b(t) are transmitted and received signals and it is necessary because it correlates the degree of co-relation between transmitted and received pulse so as to keep away from deterioration of information embedded in modulating signal. By using **Equation**
2.5, fidelity factor is calculated for Face-to-Face and Side-to-Side orientation leading to fidelity factor values 0.896 and 0.758 respectively.

![Graph](image)

**Figure 2.6:** Characterization of antenna in time domain (Study of Input signal and Impulse Response).

\[
F = \text{Max}_{\tau} \left| \frac{\int_{-\infty}^{+\infty} a(t) b(t-\tau) \, dt}{\sqrt{\int_{-\infty}^{+\infty} a(t)^2 \, dt \cdot \int_{-\infty}^{+\infty} b(t)^2 \, dt}} \right|
\]  

(2.5)

![Graph](image)

**Figure 2.7:** Group delay of UWB antenna.
To represent the level of distortion of pulse signal, group delay responses are carried out which are shown in Figure 2.7. From the figure it can be concluded that group delay is almost constant which indicates that phase constant is also almost linear which reduces the degree of distortion.

2.4.3 Analysis of gain, radiation efficiency and radiation pattern

![Figure 2.8: Radiation efficiency and Gain (UWB antenna).](image)

Figure 2.8 represents gain vs frequency and radiation efficiency. Gain of the UWB antenna varies from 2.56dBi to 4.98dBi with maximum radiation efficiency of 81%. Figure 2.9 shows setup of gain measurement of proposed antenna with two identical antennas, one as transmitter (antenna no.1) and other as receiver (antenna no.2). Gain of antenna is calculated by Equation 2.6 known as Friis Transmission equation where known power is transmitted and received power is measured. Since transmitter and receiver are identical antennas, their gains are also abbreviated the same as \( G_P \) (\( G_T = G_R = G_P \)). 'X' is the distance between the dual antennas and by selecting frequencies in the UWB band
\[
Pr = P_T G_T G_R \frac{\lambda^2}{(4\pi X)^2} \\
G_P = 4\pi X f \sqrt{P_R} / k \sqrt{P_T}
\]  
(2.6)  
(2.7)

**Figure 2.9:** Gain measurement setup with dual identical antennas.

**Figure 2.10:** Radiation Pattern in dB at 6.85GHz (a) E(Electric)-plane (b) H(Magnetic)-plane.
including notch band, gain V s frequency is plotted which is calculated by Equation 2.7 as shown in Figure 2.8. Figure 2.10 represents radiation pattern in both E(Electric)-plane (yz-plane) and H(Magnetic)-plane (xz-plane) with co-polarization and cross-polarization in both planes. Radiation pattern are simulated at designed frequency of 6.85GHz. Radiation pattern in Electric field-plane and Magnetic field-plane exhibits dipole like pattern and omni-directional pattern respectively.

2.5 UWB Antenna with Single Notched-Band Characteristics
Figure 2.11: Ultra wideband Monopole Antennas with Single band-Notched function.

Figure 2.11 shows various ultra wideband monopole antennas with single notched-band function. Figure 2.11(2.10)-(2.70) represents single notch band characteristics including filters with L-shaped slot, rectangular slot, exciting resonant frequency by electromagnetic coupling theory or by introduction of T-shaped stub either to eliminate WiMAX band or
for WLAN band [84]-[142]. Rogers RT Duroid5870 and Rogers RT Duroid5880 microwave substrate with low relative permittivity of 2.33 supports features such as wideband characteristics, stable radiation pattern with respect to frequency, four circular antennas with two symmetrical inverted L-cuts, patch with circular cut downward (low circular), patch with circular cut directed upwards (high circular) and patch with H shaped cut are proposed in [84] which are shown in Figure 2.11(2.10-2.13). As shown in Figure 2.11(2.10), antenna with pair of inverted L-cuts has most selective notched band and best impedance matching. A dual printed trapezoidal patch dipole antenna with single notched band characteristics is presented in Figure 2.11(2.16). Dual trapezoidal, one printed as radiating patch and other as ground plane, T-shape slits are etched on both the trapezoidal structure. Above said antenna satisfies the need of wireless communication exhibits good measured group delay, VSWR, gain/radiation efficiency and time domain characteristics satisfying requirement for wireless communication system [87]. A compact UWB antenna with dimension 19.2mm×38mm printed on RT Duroid5880 shown in Figure 2.11(2.17), consist of an elliptical space removed out from the ground plane and a microstrip line with semi circular shaped loop stub forming UWB antenna by removing C-type slot from the ground plane leading to one notched-band characteristics for WLAN (5.15GHz-5.825GHz) is obtained [88]. Annular ring UWB antenna with partial annular slot is embedded at the lower portion as shown in Figure 2.11(2.18) of ring radiator leading to high impedance at notch frequency at 5.5GHz [89]. Elliptical shape UWB antenna with bandwidth of 2.76GHz-17.68GHz for VSWR≤2 shown in Figure 2.11(2.20) with single notched-band characteristics which is gained by etching U-type slot on the radiation area [91]. Arc shaped stepped rectangular patch connected to a microstrip feed-line and conducting ground-plane on opposite plane of microwave-substrate as shown in Figure 2.11(2.22) at the middle of the ground plane, vertical metal strip connected via rectangular ring is embedded in the excavate-shape slot to obtain notch function [93]. By etching half-shape ellipse on the rectangular radiation patch and removing pentagonal-shaped slot in the ground plane, dual notched-band characteristics antenna covering lower WLAN band (2.4GHz) and ultra wideband band is obtained. By inserting T-shaped stub on the radiating patch intended WLAN band is removed which interfere with operating UWB band [95]. Single notch UWB antenna with λ/4 semicircular slot on radiating patch exhibits good measured and
simulated omni-directional pattern in H (magnetic)-plane and dipole like pattern in E(electric)-plane [97]. An arrow shaped ground plane with rectangular patch etches by pair of rectangular slot obtaining increased bandwidth from 2.54GHz-25.70GHz. Furthermore as shown in Figure 2.11(2.27), a pair of L-type slots on the Radiation patch provides WLAN notched-band function [98]. By application of Particle-Swarm optimization method for the utmost Mode-Coupling and better operating frequency for a comparatively smaller tapered length, a circular band notched radiating patch with raised cosine–tapered ground plane results which are shown in Figure 2.11(2.32) for ultra wideband function [103]. A semi-circular disc with a rectangle patch with dual steps and circular slit forming radiating patch in the ground plane exhibit UWB characteristics which are shown in Figure 2.11(2.37) and single notch band function is obtained by cutting arc-shape slot on the radiation patch [108]. Mirrored C-shaped slot on the square radiating area with rectangular ground plane is capable of obtaining single WLAN notched function [109]. UWB antenna with rectangular patch chamfered at the bottom edge as shown in Figure.2.11(2.39) and a slit is created in ground bottom edge to improve matching is reported in [110]. Furthermore, a T-type slit in the radiation patch, compact antenna with T-type stub within the T-type slit in the radiation patch further provides improved impedance matching over the ultra wideband which also increases the current path leading to antenna compactness. A T-type stub within the T-type slit in the radiation patch provides strong notched-band rejection with VSWR=26 and is also tuned over a wide tunable frequency ranging from 3.56GHz to 6.81GHz. A circular patch antenna comprising of chamfered ground plane represented by Figure 2.11(2.43) with the intended band notched function for WLAN is obtained by inserting pair of square ring resonator [113]. Electromagnetic coupling theory either between radiation patch and parasitic element or between ground plane and parasitic element results in single notched-band ultra wideband antenna function represented by Figure 2.11(2.14)-(2.15), Figure 2.11(2.35) and Figure 2.11(2.45)-(2.52). As mentioned in Figure 2.11(2.14), the radiating element consist of an elliptical slot which is fed by an elliptical open defunct micro strip line which is further connected to 50Ω microstrip of width=2mm and the band notched characteristics is obtain by inserting parasitic inverted U-strip to the ground plane [85]. Also by embedding semicircular annular strip in the ground plane with circular slot as represented in Figure 2.11(2.15) which is equal to half wave
length for frequency 4.8GHz with circular radiating patch is reported in [86]. Improved impedance bandwidth can also be enhanced by providing extra current path by means of etching slots in the ground plane as represented in Figure 2.11(2.35). By analysis of equivalent circuit theory of radiation patch antenna, the above said enhancement is due to change in passive element parameters of capacitor and inductor. Moreover, by placement of S-type parasitic element inside the square-type ring, electromagnetic coupling occurs between S-type parasitic element and square-type ring which excites the radiating stub and also acts as half-wave parasitic element. On the other hand, single notched-band function is obtained due to electromagnetic coupling current density is more concentrated around S-shaped coupled strip resulting high attenuation near the notched-band [106]. A half ellipse with parasitic patch of elliptical shape as shown in Figure 2.11(2.46) with truncated ground plane provides ultra wideband antenna with WLAN notched-band function is achieved [117]. Antenna with a spade-shaped ultra wideband patch on the radiation patch and two U-shaped SIR (stepped-impedance resonator) represented by Figure 2.11(2.48) around the feed line with rectangular ground plane provides UWB characteristics with band-notched function [119]. Variable frequency band-notch characteristics UWB antenna is reported in [123] which is obtained by insertion of dual slits on both sides of the microstrip-feed on the ground plane. On the opposite plane of the radiation patch, parasitic element with tailored H-type conductor having variable dimension geometry is applied to generate notched-band function which also includes controlling of impedance bandwidth. CPW feed microstrip antennas are reported in [124]-[140], where a desired notch band characteristics as shown in fig 2.11(2.54): stretched out portion of U-shape slit with its center portion merging with microstrip-feed is responsible for removal of WLAN band. As reported in [128], Removal of C-shaped slit from round-shape radiation patch on one plane and round-shape ground plane on opposite side results in WLAN band-rejection function. Also by cutting elliptical slit in the ground plane with hexagonal plane and by etching C-type slit on radiation patch single notched band UWB antenna is obtained [129]. Monopole like slot with a band-notched structure comprising of coplanar waveguide (CPW) fed antenna is reported in [137]. Insertion of spur-lines in the fork-shaped feed-structure with open stub which is grounded within the slot results to controllable notched-frequency/bandwidth [137]. CPW (Coplanar waveguide) monopole antenna comprising of a fractal radiation patch in which a
FTSE (folded T-shaped element) is embedded as reported in [142]. Number of fractal unit cells is responsible for impedance match and FTSE provides WLAN band-notched function. Also to enhance bandwidth of ultra wideband antenna applications is achieved by two rectangle-notches in the ground plane.

### 2.6 UWB Antenna with Dual Notched-Band Characteristics
Figure 2.12: UWB Monopole planar antennas with dual notch characteristics.

Figure 2.12(2.10)-(2.41) represent UWB antenna with two-notched band function. In order to achieve two notched-band functions, rectangular slot of either C-shaped or U-shaped is removed on the radiation patch or on the 50Ω-microstrip feed. Moreover, two notched-band functions are also obtained by SRR (split ring resonator) or CSRR (complimentary split ring resonator). Above said techniques are reported in [143]-[175] which are discussed below. In [143], E-ring shaped radiation patch antenna along with rectangular-ground plane is proposed. First frequency notched-band function is obtained by U-ring shaped etched structure on radiation monopole which is responsible for WiMAX band notch and by inserting a rectangular ring in the center of it an E-ring shaped radiating patch is created and a dual notch function is achieved as shown in Figure 2.12(2.10). Radiation pattern indicating omni-directional pattern in H(magnetic)-plane and dipole like pattern in E(Electric)-plane. As reported in [145], a ground plane of dimension 31mm×31mm is
etched with rectangular shape and two triangular slots which results in creating relatively wide frequency band since the rectangular slots affects the middle frequency mode, while the two triangular slots influence the higher frequency mode. As shown in Figure 2.12(2.12), the end of the 50 ohm microstrip feed line is connected to a ladder-like conducting patch so that good impedance matching with enhanced bandwidth is obtained by introducing pair of L-type slits on the ground plane, two notched-band antenna covering ultra wideband impedance bandwidth is obtained with removal of WiMAX and WLAN band which interferes with UWB band. Different techniques have been reported in literature regarding two notched-band functions. Etching E-type/U-type slit on the radiation patch and ground plane as observed in Figure 2.12(2.13) results in antenna covering ultra wideband frequencies with two notched-band function. By adjusting the length of the slots, individual notched bands are controlled independently and by varying the thickness of the etched slots, bandwidth can be varied. Two U-type slits on the radiation patch is capable of generating two notched frequencies band for WiMAX (3.5GHz)/WLAN (5.5GHz). Both the U-type slits are etched out from radiation patch with stair-case like structure placed at the bottom symmetrically which is also fed by optimized microstrip-feed (50Ω) and on the other side of microwave substrate with rectangular ground plane as depicted in Figure 2.12(2.14). Dual U-type resonators [148], one in the microstrip-feed and other on the radiation patch as shown in Figure 2.12(2.15) results in notched-bands for WiMAX/WLAN bands centered at 3GHz and 5GHz respectively. Two notched-band functional ultra wideband as reported in [150] are also designed by etching U-type slit in the feed which is connected to circular patch and with etched dual L-type slot in the ground plane as shown by Figure 2.12(2.17). As depicted in Figure 2.12(2.18), bandwidth enhancement for a rectangular profile patch is obtained by etching two rectangular-slits on the ground plane and by inserting Γ-shaped stub along with customized G-type DGS in the radiation patch and microstrip-feed respectively, intended notched-bands with center frequencies 3.50GHz/5.50GHz are resulted along with wider impedance bandwidth [151]. As shown in Figure 2.12(2.22), two of Y-shaped strips in the annular ring and removing an Ω-shaped slit on the patch, dual notched-band function for intended WiMAX/WLAN is achieved [155]. A trapezoid shape radiating patch with rectangular ground plane forms UWB antenna with U-T type stubs are inserted in two trapezoid-geometry slits of the radiating
plane as shown in Figure 2.12(2.28). As reported in [162] ultra wideband antenna with two notched-function antenna is obtained by C-L type etched slot/extrude stub in the radiation/ground plane is achieved as represented in Figure 2.12(2.29). Elliptical ring-shape radiation patch containing rectangular ground plane on opposite side of the microwave-substrate covers lower frequency application which includes band 2.40GHz-2.50GHz (Bluetooth) and ultra wideband (3.10GHz-10.60GHz). Two interfering bands Bluetooth/WLAN in the operating band are eliminated by triangular resonator/meander DGS which are centered at 2.86GHz/5.51GHz is shown in Figure 2.12(2.34). A radiating semi-circular patch with dual-steps on the front side and a rectangular ground plane form the ultra wideband antenna. A complimentary SRR (CSSR) is constructed as represented in Figure 2.12(2.38), by removing Dual Square with same centered split rings with tiny cuts which are placed on either sides of each ring in the metal cover. CSRR is inspired on Babinet principle, and as occurs with the SRR, it also exhibits quasi-static resonance. Total dimension of the CSRR is approximately equal to half of the guided wavelength at the notched frequency [172]. Quasistatic-resonance is one of the eye-catching features of CSRR. Property of negative-permittivity of CSRR based technique results in notched-band function by filtering undesired frequencies. A simple circular patch antenna with rectangular ground plane is shown in Figure 2.12(2.39). By removing CSRR (complimentary split ring resonator) on the radiation patch, dual notched-band function ultra wideband antenna is reported in [173]. A CPW-feed ultra-wideband antenna with Bluetooth applications is reported in [174]. By etching complementary circular SRR at the underneath boundary of the radiation patch along with the T-stub connected to the top of radiation patch as shown in Figure 2.12(2.40) leads to two notched-band functional antenna targeted for WiMAX/WLAN elimination band with lower frequency Bluetooth applications. Annular patch antenna with rectangular notch on the top of the ground is shown in Figure 2.12(2.41) which also includes C-type slit of about 0.58λ for required frequency of 3.5GHz along with CSRR structure etched in the ground plane to obtain WLAN notched-band function [175].

2.7 Ultra-Wideband Antennas with Two Notched-Band Function Based on CPW Feed, Electromagnetic coupling Theory (ECT) with Enhanced Bandwidth
Figure 2.13: Dual notched-band UWB Monopole Planar Antennas.

Figure 2.13(2.10)-(2.25) represents dual notched band characteristics UWB antenna with coplanar waveguide feed [176]-[197]. A hexagon radiating patch with a circular slotted ground plane with two notched band function is represented in Figure 2.13(2.13). Addition of pair of bent L-type structure to the symmetric slot-ground as shown in Figure 2.13(2.13) results in two notched-band function, one is WiMAX (3.30GHz-3.70GHz) and other is WLAN (5.150GHz-5.825GHz) [179]. Dual notch-band characteristics are also obtained by removing C-type slit on the radiation patch and two L-type parasitic strips in the ground-plane [180]. By using two diamond-shaped stepped impedance resonators on the radiation patch as shown in Figure 2.13(2.21), two notched-band functional ultra wideband antennas is obtained. By using upper and lower SIR on the radiation patch of a CPW feed UWB antenna, dual notched band characteristics are obtained [188]. A wide frequency range (2.85GHZ-15.4GHz) CPW fed UWB antenna with elliptical path with chamfered edges across the ground plane at 45 degree are presented in Figure 2.13(2.24). By insertion of two
slots, one with two L-type on the radiation patch and other on the 50Ω-microstrip with inversion of U-type leads to dual-notched ultra wideband antenna [190]. As reported in [191], a C-type and a tailored π-shaped slit removed from the patch yields two notched-bands at the center frequencies of 3.5GHz and 5.5GHz in the ultra wideband region which is shown in Figure 2.13(2.25). Impedance bandwidth of antenna with radiation patches and ground plane having the shape of a rectangle covers ultra wideband frequencies from 3.10GHz-10.20GHz [192]. Bandwidth of the antenna is increased by etching pair of rectangular-ring type slit in the ground plane and new fractional bandwidth covers 2.80GHz-17.50GHz. To convert the above said enhanced bandwidth antenna to two notched function antenna, a set of inverted T-type and inverted Ω-type slits are removed from radiation patch and ground plane respectively which are represented by Figure 2.13(2.26). The antenna with a square radiation patch along with a V-type embedded strip over rectangular ground plane as observed in Figure 2.13(2.27) covers enhanced impedance bandwidth from 2.88GHz-17.85GHz. Moreover, two notched-band enhanced bandwidth antenna results by etching out pair of L-type slit along with E-type slit on the radiation patch as reported in [193]. A compact antenna of size [194] (0.15×0.25) (k/f) at f=4.20GHz and 'k' being velocity of light in air with fork-type slot over the ground plane functions as ultra wideband antenna with operating band increased by 128.45% also functions as two notched-band antenna obtained by removing coupled inverted U-ring strip on the radiation patch as depicted by Figure 2.13(2.28). Ultra wideband antenna with four equal-sided radiation patch in addition with hook-type slot along with customized ground-plane with an inverted anchor-type slit and two Γ-type added strips inside the rectangular slit in the ground-plane as shown in Figure 2.13(2.29) leads to dual notched-band function ultra wideband antenna with wider-impedance enhancement by 130.20% [195]. As reported in [198]-[209], dual notch characteristics UWB antennas are presented with electromagnetic coupling theory (ECT). Wider fractional bandwidth of additional 125% are the results of insertion of rotated T-type ring slit on rectangular radiation patch which is in turn is covered C-type slit. To achieve intended two notched-band functional antenna, a rotated T-type slit which is covered by C-type slit on the radiation patch and by embedding rotated T-type ECT structure within the rotated T-type slit on the radiation patch as depicted in Figure 2.13(2.31), two notched-band functional antenna with wider bandwidth is reported
in [197]. As reported in [202], additional enhanced bandwidth is obtained by etching out dual-notch from the lower corner of radiation patch as shown in Figure 2.13(2.36) which is result of ECT between radiation patch and ground plane. Embedding two T/U-type stub on radiation patch and near the microstrip feed respectively, two notched-bands centered at 3.60GHz and 5.50GHz respectively are obtained. Two notched-function ultra wideband with ECT to increase impedance bandwidth of the antenna is reported in [203]. A slotted rectangular radiation patch with two rotated L-type slit and rotated T-type stub results in dual notched-band functional antenna as shown in Figure 2.13(2.37). A two notched-band utility ultra wideband antenna is reported in [204] which consist of modified T-type slit and a ground plane with dual E-type slits along with W-type conductor backed-plane is shown in Figure 2.13[2.38]. First notch is obtained by W-shaped conductor backed plane where electromagnetic coupling occurs between ground and W-shaped at 3.9GHz and T-shaped stub provides second notch centered at 5.5GHz. Two E-type slits over the ground plane are accountable for wider impedance-bandwidth. The design is represented by Figure 2.13(2.38). Stepped shaped patch and dual-rectangular slits over the ground plane for wider impedance bandwidth of 155% is reported in [205]. Dual notched band characteristics is also obtained by eliminating U-type slit on the radiation patch and butterfly-shaped conducting-element backed-plane for ECT is shown in Figure 2.13(2.39). Fractal shaped dual notch UWB antennas are reported in [210]-[214]. The multiple resonance characteristics with Koch fractal geometry and rectangular ground plane from ultra wideband antenna and dual notched-band function is obtained by embedding pair of C-type slits on the radiation patch.

### 2.8 UWB Antenna with Triple and Quadruple Notched-Band Characteristics

![Diagram of UWB Antenna with Triple and Quadruple Notched-Band Characteristics](image)
Figure 2.14: UWB Monopole Planar Antennas with triple and Quadra band notch function.

Figure 2.14(2.10)-(2.24) represents triple notch band antennas and Figure 2.14(2.25)-(2.26) represents Quadra notched band antennas [215]-[232]. A ultra wideband monopole antenna with tri-notched band function is represented in Figure 2.14(2.10). The three notched bands i.e., WiMAX (3.3GHz-3.7GHz), WLAN IEEE802.11a (5.15GHz-5.825GHz) and X-band satellite communication system (7.25GHz-8.395GHz) is obtained by incorporating an etched inverted U-slot, C-slot over the radiation patch and U-slit on the 50Ω feed line. As reported in [217], rectangular path with two bevels at the bottom and rectangle-ground plane with dual levels around the higher edge to improve the operating band around
frequency limit of 3.0GHz is etched on Microwave-FR4 substrate with height of 0.8mm with antenna dimension 31mm×22mm. As shown in Figure 2.14(2.11), Triple notched band functional ultra wideband antenna is obtained by removing dual circular shape slits corresponding to one-half the wavelength on the radiation patch for 3.3GHz-3.70GHz/5.150GHz-5.85GHz band and for the third notched-band dual C-type slit in the ground plane results 7.10GHz-7.90GHz downlink satellite-communication application. By removing dual circular slits on the radiation patch and a couple of C-type slit over the ground plane, three notched-band function ultra wideband antenna is resulted as shown in Figure 2.14(2.13). As shown in Figure 2.14(2.16), triple notched band characteristics are also obtained by 3 pair of split ring resonators along with the 50Ω microstrip feed line [221]. As shown in Figure 2.14(2.22), the ultra wideband antenna comprises of a rectangle plane as radiation patch with set of steps on the feed edge, rotated stair-shape ground plane and a CPW-feed line. The staircase structure increases the impedance bandwidth. By introducing C-type slit on the main radiation patch, Complimentary Split Ring Resonator at the ground plane and rotated U-type slit at the middle of the radiation patch results in fine band-rejection of WiMAX/WLAN/X-band satellite bands [226]. Quadruple antenna (U-notched band characteristics) is reported in [231]-[232]. Three circular slits on the radiation patch with etched pair of C-type slits over the ground plane as shown in Figure 2.14(2.26) results in four notches intended for 3.3GHz-3.7GHz (WiMAX band), 5.150GHz-5.350GHz (lower WLAN band), 5.725GHz-5.875GHz (higher WLAN band) and 7.10GHz-7.76GHz (X-band downlink satellite communication band) [232]. By etching three C-shaped slot on the microstrip line, quadruple notched-band ultra wideband antenna is obtained as shown in Figure 2.14(2.26). [234]-[241] represents antenna on Silicon Substrate. A multi band antenna designed on silicon microwave substrate is reported in [235] which is applicable working in sub-bands around high frequency bandwidth of 30GHz-150GHz. This antenna has application in satellite communication system above 30GHz. As reported in [236], P-shaped wearable antenna is designed for body centric wireless communication on various substrates such as RTDuroid, Diamond, Gallium Arsenide and Silicon. Driven loop or dipole antennas are developed on silicon substrate for 94GHz imaging applications with high gain Quasi-Yagi printed antennas. Antenna has maximum gain of 8.1dBi [237]. For better radiation, less conductivity or high restivity materials are preferred. In order to obtain
high resistivity, Silicon-dioxide layer is one of the solutions as reported in [238]. Another antenna as reported in [239], for integration of millimeter wavelengths antenna on silicon technologies for high rate communication and sensing applications. QUBIC 4X copper technology is used for integration of NXP semiconductor. By using stacked capacitor and spiral inductor, silicon based on-chip antennas are designed [241]. Antenna exhibits good near field performance. Phase shifters for various applications are reported in [242]-[254]. Multi-stage negative group delay which is based on Field Effect Transistor in synchronization with series resonant circuit for phase shift of 90°/45° is reported in [242]. A passive phase shifter for phase shift ranging 25°- 48° with compact dimension of 25×20 mm² is reported in [243]. To improve the radiation characteristics, double rhombus antenna with a 180° microstrip phase shifter is reported in [244]. Stable radiations are achieved when modified two-element array is used with phase shifter and are useful for ultra wideband phased arrays and power combiners. Differential phase imbalance of ±10° with less than 1dB insertion loss phase shifter is reported in [245] which operate in band from 4.2GHz-11.0GHz. This phase shift of 180° is obtained by adding four ended stubs to the microstrip patches and CPW. Differential phase shift of 90°, 180° and 270° operating in UWB band (3.10GHz-1060GHz) with differential imbalance of less than ±8° and also insertion loss less than 0.8dB. Device based on electro magnetic coupling between top and bottom microstrip patches via slot located in the middle layer which forms the ground plane provides phase shift. The other type of phase shifter where quarter wavelength parallel coupled lines combine with short-ended stub structure and an impedance transformer provides a phase shift of 90° and 180°. Reported phase shifter operates in UWB band with less than ±11° differential phase imbalance and less than 1.2dB insertion loss [247]. By using shunt quarter wavelength stubs in the resonating branches and transmission lines in the reference branches, phase shift from 20° to 70° is achieved as reported in [252]. On of the feature of the phase shifter is measured imbalance which is less than 0.3dB. Phase shifter working in 3.10GHz-12.0GHz uses double microstrip-slot transitions for use in ±90° phase shifter as reported in [253].

2.9 Antenna Characterization of Triple Notched-Band Antenna

In order to understand the triple notched band characteristics, characterization of UWB antenna is carried out where UWB covers impedance bandwidth of 3.1GHz-10.6GHz.
Existing wireless communication system which includes WiMAX (Worldwide-interoperability for microwave-access) operating in 3.3GHz-3.8GHz, WLAN (Wireless local area network) operating in 5.15GHz-5.825GHz band and X-band downlink satellite communication system occupying bandwidth of 7.1GHz-7.9GHz band interferes with UWB band. To avoid such interference, UWB antenna with triple band notch characteristics which filters out above said interfering bands is carried out.

![Triple notched band UWB antenna](image)

**Figure 2.15:** Triple notched band UWB antenna (a) Radiation patch (b) Ground plane.

Triple notched band antenna represented in Figure 2.15 [229] is taken as example for antenna characterization which is fabricated on FR4 substrate with dimension 30mm×35mm. On one side of the substrate, radiating patch comprising of circular annular ring with two elliptical slit on the radiation patch and couple of SRR (split ring resonator) near the 50Ω-microstrip line is shown in Figure 2.15(a). Opposite plane of the microwave-substrate, rectangle ground-plane with pair of etched slots is shown in Figure 2.15(b). The bigger and smaller elliptical slot on the radiation patch is responsible for WiMAX/WLAN notched bands whereby, pair of SRR near the feed line notched X band downlink satellite-communication band. Slit on the ground plane is significant responsible for wide band function which also produces additional path for surface current resulting in extra resonances at elevated frequencies.
2.9.1 VSWR and surface current density distribution

Figure 2.16 shows VSWR response of triple notched band UWB antenna. It can be concluded that in the entire operating band VSWR ratio is below 2 except in the notched bands. Maximum VSWR at 3.58GHz, 5.35GHz and 7.65GHz is 6.32, 5.14 and 9.70 respectively. The value of \( f_{\text{FirstNotch}} \), \( f_{\text{SecondNotch}} \) and \( f_{\text{ThirdNotch}} \) are calculated at 3.58, 5.35 and 7.65 GHz respectively by following equations

\[
L_{\text{First Notch}} = \frac{C}{2 \times f_{\text{FirstNotch}} \sqrt{\varepsilon_{\text{eff}}}} \\
L_{\text{Second Notch}} = \frac{C}{2 \times f_{\text{SecondNotch}} \sqrt{\varepsilon_{\text{eff}}}} \\
L_{\text{Third Notch}} = \frac{C}{2 \times f_{\text{ThirdNotch}} \sqrt{\varepsilon_{\text{eff}}}}
\]

where 'c' is velocity of Electromagnetic Wave in free space and is given by \( c = 3 \times 10^8 \) m/sec.

In order to understand the concept behind above mentioned triple notched-band performance, current distribution for the antenna at the notched-band frequencies are (3.58GHz, 5.35GHz and 7.65 GHz) presented in Figure 2.17. As illustrated in Figure 2.17(a) for the first notched-band current density is concentrated more at the bigger
elliptical slot (WiMAX), for the second notched-band current density distribution is concentrated at the inner and outer edge of the smaller elliptical slot (WLAN) as shown in Figure 2.17(b) and Figure 2.17(c) represents current density concentration at the SRR (X-band). Furthermore, the powerful current density-distributions around slits/SRR at the notched frequency lead to near field radiation, which results in

![Current density distribution](image)

**Figure 2.17:** Current density distribution at (a) 3.58GHz (b) 5.35GHz (c) 7.65GHz.

reflection of transmitted power to return back to source which in turn prevents radiations and hence notched-band function is obtained. It is also evident from Figure 2.17(a)-(c) that there exists almost nil coupling between the notched-elements for a fixed notched frequency and can be concluded that each notched-bands are controllable independently. For all other frequencies other than the intended notched-band, current-density distribution is evenly spread over the radiation surface.

2.9.2 Time domain analysis

Pulse distortion which is one of the characteristics of UWB signals is essentially determined by their bandwidth. Impulse response of triple notched band antenna is carried out by placing two same antennas FF (Face-to-Face) and SS (Side-to-Side) orientations at distance of 250mm. By maintaining good impedance match except in the notched bands reflection loss are minimized to avoid pulse distortion. Due to mismatch between the input pulse and the antenna a slight acceptable signal distortion is observed in Figure 2.18. To judge the distortion of the transmitted pulses, group delay study is carried out as shown in Figure 2.19. For the perfect transmission of pulses, group delay should be constant within
the operating entire band. For the above said antenna, Group delay is almost constant in the entire operating band.

**Figure 2.18:** Time domain analysis (Input signal and Impulse Response).

**Figure 2.19:** Group delay of triple notched band UWB antenna.
2.9.3 Result discussion on gain, radiation efficiency and radiation pattern

Gain measurement of the antenna was carried out by two antenna method [255]-[263]. Gain of the antenna with radiation efficiency along notched-bands is shown in Figure 2.20. Drop in peak gain can be observed at 3.54GHz, 5.30GHz and 7.60GHz with values of 8.65, 6.34 and 4.12. As it is expected that at the three notched band frequencies gain falls below 0dBi confirming of non radiation mode of the antenna. However, antenna maintains peak gain values of 3.20 to 4.79 in the operating band as confirmed by Figure 2.20. Antenna exhibits good maximum radiation efficiency of around 90% and reduces at 3.25GHz, 5.58GHz and 7.8GHz with corresponding values of 18%, 21% and 26% respectively.

![Graph showing Gain vs Frequency and Radiation Efficiency vs Frequency](image)

**Figure 2.20:** Gain and Radiation Efficiency of Triple notched band UWB antenna.

![Radiation Pattern in dB at 4.2GHz](image)

**Figure 2.21:** Radiation Pattern in dB at 4.2GHz (a) E(Electric)-plane (b) H(magnetic)-plane.
Radiation patterns are presented in two principle planes E(Electric)-plane and H(magnetic)-plane. Normalized radiation pattern in E(Electric)-plane and H(Magnetic)-plane are simulated at 4.2GHz as shown in Figure 2.21. Over the non notched radiation band, antenna exhibits dipole like pattern with admissible cross polarization in E-plane and omni-directional pattern also with admissible cross polarization in H-plane.

2.10 Summary
In this chapter, UWB antennas with single/dual/triple notched band characteristics for UWB applications have been presented. This chapter also discusses the introduction of planar UWB antenna followed by investigation of research work several research work which is related to extension of wide bandwidth including dual and triple notched-band function. This chapter also discusses the theory behind UWB antenna and Phase Shifter on Silicon-Substrate. This chapter also discusses research work related to notched-band UWB antennas. Moreover, to authenticate the design methodology, two antennas which are reported in [209] and [229] are characterized on both frequency and time domain so that the proposed research can be carried out which are discussed in upcoming chapters.