Earlier part of this chapter is devoted for the detailed literature review about the planar slot antenna. The evolution of a reduced size UWB slot antenna design is presented. This antenna overcomes the disadvantage of pattern deterioration at the higher frequencies of antennas described in previous chapters. For ease of fabrication and better integration, a CPW feed is employed. The surface current distributions on the antenna and their radiation patterns at the resonant modes are analyzed in detail. From the detailed experimental and simulation studies, the design equations for the planar slot UWB antenna are derived. To reduce the interference with the conventional WLAN, a notch band is also introduced. Time domain analysis of these antennas is also conducted to study the suitability of these antennas for pulse based applications.
4.1 Review on UWB planar Slot Antennas

A slot antenna comprises of a slot of appropriate shape on a thin sheet of metal. The slot radiates electromagnetic energy bidirectionally when excited by a voltage source. Slot antenna is considered as the compliment of dipole antenna and regarded as the magnetic of monopoles in view of the EM duality. Slot antenna can be fabricated on a metallic strip very easily. Usually the slot length is half of the wavelength at the desired frequency and the width is a small fraction of wavelength. The antenna is frequently compared to a conventional half-wave dipole consisting of two metal strips. The physical dimensions of the metal strips are just compliment of the slot antenna sheet. This type of antenna is called the complementary dipole. The electric field distribution in the slot can be obtained from the relationship between the slot and complementary wire antennas, as established by Babinet [1].

A U-shaped slotted patch was experimentally investigated in [2] and an impedance bandwidth of 27% from 1.565-2.065 GHz, was obtained. Several researchers have attempted similar approaches with microstrip patch antennas, a detailed account of which has been compiled in [3] and [4].

Another technique is to excite a narrow rectangular slot with a simple microstrip feed line as in [5] and [6]. In [5], the feed point is shifted from the center of the slot and is short circuited through the dielectric substrate. A similar technique of feed point shifting close to the slot end was used in [6]. In both cases, the offset of the feed point lead to perfect impedance match in a narrow frequency band and obtained an impedance bandwidth of approximately 20%.

When a T-shaped microstrip tuning stub is used to excite a wide rectangular aperture, a relatively broad bandwidth is noted (58%) from 1.5 to 3.2GHz [7]. Similarly, modifications in the shape of the slot can also result in broadband
operation as in [8] where a semi-circular slot and a protruding square shape is used to realize a bandwidth of 46%.

A kind of tapered slot antenna with planar structure, which was called the Vivaldi antenna, was proposed by P. J. Gibson [9] in 1979. This antenna has a wide bandwidth and a medium gain, but worked as an end-fire antenna. Its longitudinal dimension is large and impedance bandwidth is inherently limited by the microstrip to slotline transition. A printed two-side-antipodal exponential tapered slot antenna proposed by E. Gazit [10] has resolved the transition problem, though with a relatively higher cross-polarization level. Later, the balanced antipodal Vivaldi tapered slot antenna introduced by J. D. S. Langley [11] restrained the cross polarization to be less than -17 dB, with a bandwidth of 15 : 1, covering frequencies from 1.3–20 GHz.

In recent years, many researchers have been engaged in the printed wide-slot antenna and have realized the ultra wide band property through the combination of changing the slot shape and using different feeding structures. The wide-slot antenna is fed by a cross-shaped feeding with a cross shaped stub at the end instead of the common open microstrip feeder. It is equivalent to introducing a resonance circuit and hence resulting in an impedance bandwidth of 98% [12]. The slot antenna fed by a fan shaped stub together with a strip line has achieved a bandwidth of 114% by optimizing the length of the stub and the size of the fan-shape [13].

In [14], a rectangular patch in the middle of the rectangular slot is used to achieve a measured impedance bandwidth of 111%. By adding a rectangular copper sheet on one side of the microstrip to adjust the port impedance of the antenna, its impedance bandwidth extends to 135.7%, covering frequencies 2.3–12 GHz [15]. The printed wide-slot antenna also has been designed to use
various shapes of the guide strip terminal of its CPW feeder to excite the slot, and accordingly obtain the broadening of its impedance bandwidth.

Another type of printed slot antenna is the printed bowtie slot antenna, which has by virtue of simple configuration, wide bandwidth, low cross polarization level and high gain [16, 17]. In [16], impedance bandwidth is widened by using a linearly tapered slot at the joint of the coplanar waveguide and the bow-tie slot. A tapered coplanar waveguide feeder can be applied for achieving an impedance bandwidth of 123% [17].

A novel planar tapered-slot-fed annular slot antenna [18] proposed by T.G. Ma utilizes a unique tapered-slot feeding structure and simultaneously possesses ultra wide bandwidth, almost uniform radiation patterns, and low profile.

An improved design of the U-shaped stub rectangular slot antenna with a tuning pad for enhancing the impedance bandwidth is proposed by D.C. Chang [19]. By properly tuning the physical size of the copper pad, a wide impedance bandwidth can be achieved for UWB applications. For 10 dB return loss, impedance bandwidth of the antenna is from 2.3 to 12 GHz (135.7%).

Pengcheng Li presented two novel designs of planar elliptical slot antennas[20]. This printed antenna fed by either microstrip line or coplanar waveguide with U-shaped tuning stub with the elliptical/circular slots offered ultrawideband characteristics.

Evangelos S.et.al presented novel circular and elliptical CPW-fed slot and mictrostip-fed antenna designs targeting the 3.1–10.6 GHz band[21]. The antennas are comprised of elliptical or circular stubs that excite similar-shaped slot apertures. Four prototypes have been examined, fabricated and experimentally tested. The
three being fed by a CPW and the fourth by a micro strip line. They exhibited a very satisfactory behavior throughout the 7.5 GHz band in terms of impedance match (VSWR 2), radiation efficiency and radiation pattern characteristics.

T.G.Ma.et.al presented a new coplanar waveguide- fed tapered ring slot antenna for ultra wideband (UWB) applications[22]. This antenna consists of a 50Ω coplanar waveguide feeding line, wideband coplanar waveguide-to-slot line transition, and a pair of curved radiating slots. The impedance bandwidth is from 3.1 GHz to more than 12 GHz. The actual operating bandwidth is, however, limited by the distortion of radiation patterns. Such pattern distortion can be attributed to the antenna mode transition and is investigated with the help of the radiation patterns in the traditional sense as well as a dimensionless normalized antenna transfer function.

An ultrawideband (UWB) stripline slot antenna is analysed in frequency and time domain by C. Marchais et al [23]. Experiments were carried out to investigate its return loss, radiation behavior, and time-domain response. The antenna offers 130% impedance bandwidth. Moreover, its 108% radiation bandwidth covers the UWB band with a linear radiated far-field phase.

Gopikrishna et al. presented a novel ultra-wideband (UWB) antenna consisting of a linear tapered slot in the ground plane and a microstrip to slotline transition [24]. The antenna possesses a wide bandwidth from 2.95–14 GHz and shows stable radiation patterns with an average gain of 3dBi throughout the band. Measured group delay and transmission characteristics indicate that the antenna has good pulse handling capabilities.

A novel ultra wideband (UWB) printed wide-slot antenna was presented by Shi Cheng et al [25]. The presented design comprises of PICA-like structures,
etched from a double-layer substrate. Compared to the original PICA, it is lower in profile, more compact and maintains comparable performance. The results show that the proposed antenna provides at least 13:1 impedance bandwidth at 10-dB return loss.

A new coplanar waveguide-fed slot antenna for ultrawideband (UWB) applications is presented by Aidin Mehdipour [26]. The UWB characteristics of the antenna are achieved through the electromagnetic coupling between two adjacent slot arms. The antenna operates with VSWR lower than 2.2 in frequency band 3.1 GHz -10.6 GHz.

D.D. Krishna et al. presented an ultra-wideband (UWB) printed slot antenna, suitable for integration with the printed circuit board (PCB) for Wireless Universal Serial-Bus (WUSB) dongle applications [27]. The design comprises of a near-rectangular slot fed by a coplanar waveguide printed on a PCB of width 20 mm. The proposed design has a large bandwidth covering the 3.1–10.6 GHz UWB band, with omnidirectional radiation patterns.

Two new low-cost, compact antennas, which operate in the upper half of the direct sequence spread spectrum UWB (DS-UWB) band, are presented by Tharaka Dissanayake [28]. These antennas are not only impedance matched, but also retain very good pattern stability over the operating band. One L-slot antenna has a planar ground plane and the other modified L-slot antenna has a ground plane consisting of a planar section and two sidewalls. Measured radiation pattern is presented to demonstrate the effect of ground plane on radiation patterns. Wideband radiation characteristics and the pattern stability of these antennas are investigated with the help of pattern stability factor (PSF).

Sunil Kumar Rajgopal presented an ultra wideband (UWB) pentagon shaped planar microstrip slot antenna that can find applications in wireless
communications [29]. Combination of the pentagon shape slot, feed line and pentagon stub are used to obtain 124% (2.65–11.30 GHz) impedance bandwidth which exceeds the UWB requirement of 110% (3.10–10.60 GHz). A ground plane of 50mm x 80 mm size is used which is similar to wireless cards for several portable wireless communication devices. The proposed antenna covers only the top 20 mm or 25% of the ground plane length, which leaves enough space for the RF circuitry. Three variations of the antenna design using the straight and rotated feed lines on two different substrates are considered. Effect of the conducting reflecting sheet on back of the antenna is investigated, which can provide directional radiation patterns but with reduced matching criteria.

A simple and compact CPW-fed ultra-wideband monopole-like slot antenna [30] was presented by X. Qing. The antenna comprises a monopole-like slot and a CPW fork-shaped feeding structure, which is etched on a FR4 printed circuit board (PCB) with an overall size of 26 mm x 29 mm x 1.5 mm. The simulation and experiment show that the proposed antenna achieves good impedance match, consistent gain, stable radiation patterns and consistent group delay over the operating bandwidth of 2.7–12.4 GHz (128.5%). Furthermore, through adding two more grounded open-circuited stubs, the proposed antenna design features band-notched characteristic in the band of 5–6 GHz while maintaining the desirable performance over lower/upper UWB bands of 3.1–4.85 GHz/6.2–9.7 GHz.

Jorge R. Costa presented a simple and compact printed antenna that exhibits adequate transient performance for ultra wideband (UWB) applications and it is further adequate for polarization diversity schemes[31]. The antenna is based on an original combination of two crossed exponentially tapered slots plus a star-shaped slot to produce a stable radiation pattern with very stable polarization over the 3.1–10.6 GHz FCC assigned band. Figure of merit like
output pulse fidelity and time window containing 90% of the transmitted energy are analyzed over the entire solid angle and showed to remain quite stable, in line with envisaged UWB system requirements. Compact dual-antenna arrangements are also analyzed in view of potential use for UWB multiple-input–multiple-output implementations.

A method to design a microstrip-fed antipodal tapered-slot antenna, which has ultra wideband performance and miniaturized dimensions was proposed by M. Amin Abbosh [32]. The proposed method modifies the antenna structure to establish a direct connection between the microstrip feeder and the radiator. That modification, which removes the need to use any transitions and/or baluns in the feeding structure, is the first step in the proposed miniaturization. In the second step of miniaturization, the radiator and ground plane are corrugated to enable further reduction in the antenna’s size without jeopardizing its performance. The simulated and measured results confirm the benefits of the adopted method in reducing the surface area of the antenna, while maintaining the ultra wideband performance.

Chow-Yen-Desmond Sim proposed a novel compact microstrip-fed slot antenna [33]. By properly loading a notch to the open-ended T-shaped slot and extending a small section to the microstrip feed line, multiple resonant frequencies are excited and merged to form large enough 10-dB return loss bandwidth (measured from 3.1 to 11.45 GHz) for ultra wideband (UWB) applications.

In applications where size, weight, cost, performance, ease of installation, and aerodynamic profile are constraints, low profile antennas like microstrip and printed slot antennas are required. Printed slot antennas fed by CPW have several advantages over microstrip patch antennas. Slot antennas exhibit wider bandwidth, lower dispersion and lower radiation loss than microstrip antennas,
and when fed by a coplanar waveguide. They also provide an easy means of parallel and series connection of active and passive elements that are required for improving the impedance match and gain [34].

4.2 Triangular slot UWB antenna

The release of Ultra Wideband (UWB) for unlicensed applications by the FCC (Federal Communication Commission) received much attention by the industries and academia. This is due to low power consumption, high secured data rate support [35]. With the rapid developments of such UWB systems, a lot of attention is being given for designing the UWB antennas. The design of an antenna at the UWB band is quite challenging one because it has to satisfy the stringent requirements such as very large impedance bandwidth, omni directional radiation pattern, constant gain, high radiation efficiency, constant group delay, low profile and easy to manufacture [36]. Interestingly the planar slot antennas with CPW fed posses the above said features with simple structure, less radiation loss, less dispersion and easy integration with monolithic microwave integrated circuits (MMIC) [37]. Hence, the CPW fed planar slot antennas [38-45] are identified as the most promising antenna design for wideband wireless applications. In planar slot antennas two parameters affect the impedance bandwidth of the antenna, the slot width and the feed structure. The wider slot provides more bandwidth and the optimum feed structure gives the good impedance matching.

In this session, design of a triangular slot antenna with ultra wide impedance band width is presented. The antenna 1 is a simple triangular slot antenna(Fig.4.1(a)). Then the transmission line is extended by a length S as shown in Fig. 4.1(b)(Antenna 2). Then a rectangle of length L and width W is top loaded on the signal strip resulting in the development of final UWB design(Antenna 2). The evolution of the antenna is shown in Fig.4.1.
Fig. 4.1 Evolution of Triangular slot UWB antenna (a) Triangular slot antenna (b) Signal strip extended Triangular slot Antenna (c) Triangular slot UWB antenna.

\( L_1 = 26\text{mm}, \ L_2 = 22.65\text{mm}, \ L_3 = 9\text{mm}, \ L_4 = 10.85\text{mm}, \ L_5 = 7\text{mm}, \ S = 2\text{mm}, \ W = 3\text{mm}, \ h = 1.6\text{mm}, \ \varepsilon_r = 4.4 \) and \( G = 0.35\text{mm} \)

### 4.2.1 Triangular slot Antenna (Antenna 1)

The antenna consists of an isosceles triangular slot of side \( L_2 \) and base \( 2L_3 + W + 2G \) etched on a square substrate of size \( L_1 \times L_1 \) having dielectric constant \( \varepsilon_r = 4.4 \), loss tangent \( \tan \delta = 0.02 \) and thickness \( h = 1.6 \) mm. The strip width (W) and gap (G) of the CPW feed are derived using standard design equations for 50Ω input impedance[47]. The top and side view of the antenna geometry is illustrated in Fig. 4.1.

Fig. 4.2. Geometry of the Antenna 1 \( (L_1 = 26\text{mm}, \ L_2 = 22.65\text{mm}, \ L_3 = 10.85\text{mm}, \ L_4 = 7\text{mm}, \ W = 3\text{mm}, \ G = 0.35\text{mm}, \ h = 1.6\text{mm} \) and \( \varepsilon_r = 4.4 \)
The reflection and transmission coefficients of the antenna shown in Fig.4.3 indicates that antenna has a poorly matched resonance at 14GHz. The reflection coefficient is only -3.8dBi. The $S_{21}$ study shows that there is some radiation at this frequency but it is not efficient. With an aim to bring matching in the operating band, transmission line of antenna 1 is extended by a length $S$ as described in the next session.

![Fig.4.3. Reflection and transmission coefficients of antenna 1](image)

**Fig.4.3. Reflection and transmission coefficients of antenna 1**

($L_1 = 26\text{mm}$, $L_2 = 22.65\text{mm}$, $L_3 = 10.85\text{mm}$, $L_4 = 7\text{mm}$, $W = 3\text{mm}$, $G = 0.35\text{mm}$, $h = 1.6\text{mm}$ and $\varepsilon_r = 4.4$)

### 4.2.2 Signal strip extended Triangular slot Antenna (Antenna 2)

In the previous section we have seen that the antenna produces a poorly matched resonance at 14 GHz. In order to improve the matching, signal strip of antenna 1 is extended by a length $S$ resulting in Antenna 2. Since $S$ is inside the slot compactness of the antenna is not at all affected.

The antenna includes an isosceles triangular slot of side $L_2$ and base $2L_3+W+2G$ etched on a square substrate of size $L_1\times L_1$ having dielectric constant $\varepsilon_r = 4.4$, loss tangent $\tan \delta = 0.02$ and thickness $h = 1.6$ mm. Signal
strip is extended by a length S. The top and side view of the antenna geometry is illustrated in Fig. 4.4.

Fig. 4.4. Geometry of the Antenna 2
\( L_1 = 26 \text{mm}, L_2 = 22.65 \text{mm}, L_3 = 10.85 \text{mm}, L_4 = 7 \text{mm}, W = 3 \text{mm}, S = 2 \text{mm}, G = 0.35 \text{mm}, h = 1.6 \text{mm and } \varepsilon_r = 4.4 \) 

Fig. 4.5. Reflection and transmission coefficients of antenna 2
\( L_1 = 26 \text{mm}, L_2 = 22.65 \text{mm}, L_3 = 10.85 \text{mm}, L_4 = 7 \text{mm}, W = 3 \text{mm}, \)
\( G = 0.35 \text{mm}, h = 1.6 \text{mm and } \varepsilon_r = 4.4 \) 

Reflection and transmission coefficients of the antenna plotted in Fig. 4.5 indicate that there is a single resonance at 13.5GHz with bandwidth ranging
from 13-14GHz. Also there is a tendency for matching around 4 GHz, ie, is improved matching is obtained than antenna 1. The transmission characteristics again confirms this result. At 13.5GHz, power received is nearly -19dBi which is very much greater than antenna 1.

To improve matching at low frequency region and to produce additional resonance in the middle frequency range, a rectangular stub is incorporated on the signal strip resulting in the development of final antenna. The combined effect of the triangular slot and rectangular stub results in the UWB operation. This is carried out in detail in the next session.

4.2.3 Triangular Slot UWB Antenna (Antenna 3)

In this section, a printed compact Coplanar Waveguide(CPW) fed triangular slot antenna for Ultra Wide Band (UWB) communication systems is presented. Design equations are implemented and validated for different substrates. The simulation and experimental studies reveal that the proposed antenna exhibits good impedance match, stable radiation patterns and constant gain throughout the operating band.

4.2.3.1 Geometry of the Triangular slot UWB Antenna

The geometry of the proposed antenna is shown in Fig.4.6. The antenna consists of an isosceles triangular slot of side $L_2$ and base $2L_3+W+2G$ etched on a square substrate of size $L_1\times L_1$ having dielectric constant $\varepsilon_r = 4.4$, loss tangent $\tan \delta = 0.02$ and thickness $h = 1.6$ mm. A rectangle of length $L$ and width $W$ is connected as shown in the figure. The spacing between the rectangle and the edge of the ground plane is $S$. The antenna is distinctive in its structure and it has simple design with less number of design parameters compared to the existing antennas in the literature.
4.2.3.2 Reflection Characteristics of the Triangular slot UWB Antenna

Fig. 4.7 illustrates the simulated and measured reflection coefficient of the optimal design of the antenna with parameters as in Fig.4.6. The -10dB bandwidth appears to span an extremely wide frequency range from 3.1GHz to 11.1GHz. The wide bandwidth is obtained by merging three resonances centered at 3.38GHz, 4.8GHz and 9.5GHz respectively. This is elaborately explained in the remaining sessions.
4.2.3.3 Parametric Analysis of the Triangular slot UWB Antenna

Further insight on the antenna performance is obtained by carrying out a detailed parametric analysis. The variation of reflection coefficients with different antenna parameters are given below.

4.2.3.3.1 Effect of rectangle length L

In order to study the effect of strip length L on the return loss characteristics, a thorough parametric analysis has been performed. Fig 4.8 shows the variation of reflection characteristics and input impedance for different strip lengths L. It is observed that without the strip (L=3), there are only two poorly matched resonances within the UWB frequency range.
Fig. 4.8. Reflection coefficient and impedances of the triangular slot antenna for different L
(a) Reflection coefficient (b) Real part of impedance (c) Imaginary part of impedance
(L₁=26mm, L₂=22.65mm, L₃=10.85mm, L₄=7mm, S=2mm, W=3mm, h=1.6mm, εᵣ = 4.4 and G=0.35mm)
As L increases, matching corresponding to the first and second resonances increases. The strip produces a third resonance and at the optimum strip length, three resonances merge together to form UWB frequency response. It can also be seen that without the strip, the antenna has very low input impedance and is highly capacitive. Increase in L improves the input impedance corresponding to the first and second resonances. Also the imaginary part is shifted towards the inductive side. The strip produces extra capacitive reactance and at the optimum design, it merges the resonances to give UWB operation. From parametric studies L is found to be $0.346 \lambda_c$ where $\lambda_c$ is the wavelength corresponding to centre frequency of the operating band.

4.2.3.3.2 Effect of gap distance S.

Variation of S, which adjusts the coupling between the radiating element and the ground plane is also studied. Variation of return losses and input impedances of the antenna for different S are shown in Fig. 4.9. It is found that good impedance matching can be obtained by enhancing the coupling between the slot and feed. When the coupling is increased to a certain value, the optimum operating bandwidth can be obtained. However, if the coupling is increased more, the impedance matching deteriorates, showing that over coupling also degrades the impedance matching. For $S=1\text{mm}$, matching is very poor for the first two resonances and real part of impedance is low ($24 \Omega$), but impedance improves with increase in S and a value of $50 \Omega$ is achieved at $S=2\text{mm}$. Also increase in S increases the inductive reactance. When $S=3\text{mm}$, real part of impedance is further increased and the imaginary part is shifted towards inductive side. From detailed analysis value of S is optimised to be $0.076 \lambda_c$ where $\lambda_c$ is the wavelength corresponding to centre frequency of the operating band.
Fig. 4.9. Reflection coefficients and impedances of the triangular slot antenna for different S. (a) Reflection coefficient (b) Real part of impedance (c) Imaginary part of impedance.

$L_1=26\text{mm}$, $L_2=22.65\text{mm}$, $L=9\text{mm}$, $L_3=10.85\text{mm}$, $L_4=7\text{mm}$, $W=3\text{mm}$, $h=1.6\text{mm}$, $\varepsilon_r=4.4$ and $G=0.35\text{mm}$
4.2.3.3.3 Effect of triangular side $L_2$

Effect of variation of $L_2$ on reflection coefficient is also conducted and shown in figure 4.10. It is found that $L_2$ mainly affects the resonances and the bandwidths are less affected. Optimum performance is obtained for $L_2=22.6$mm. From exhaustive analysis value of $L_2$ is found to be $0.87 \lambda_c$ where $\lambda_c$ is the wavelength corresponding to centre frequency of the operating band.

![Reflection coefficient of the triangular slot antenna for different $L_2$ values](image)

**Fig. 4.10.** Reflection coefficient of the triangular slot antenna for different $L_2$ values ($L_1=26$mm, $L_2=22.65$mm, $L_3=9$mm, $L_3=10.85$mm, $L_4=7$mm, $W=3$mm, $h=1.6$mm, $\varepsilon_r=4.4$ and $G=0.35$mm)

4.2.3.3.4 Effect of $L_3$

The effect of variation of reflection coefficient with different $L_3$ values are also conducted and is shown in Fig. 4.11. It is found that compared to $L_2$, $L_3$ affects the resonant frequencies also. From detailed analysis value of $L_3$ is found to be $0.417 \lambda_c$ where $\lambda_c$ is the wavelength corresponding to centre frequency of the operating band.
Fig. 4.11  Reflection coefficient of the triangular slot antenna for different \( L_3 \) values (\( L_1=26\text{mm}, L_2=22.65\text{mm}, L=9\text{mm}, L_4=7\text{mm}, W=3\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4 \) and \( G=0.35\text{mm} \))

### 4.2.3.5 Field distributions and Radiation patterns of the Triangular slot UWB Antenna

From the spectrum of impedance performance, it can be seen that there are three resonances at 3.38, 4.8, and 9.5 GHz. These resonances correspond to the different modes of field distribution and play important roles on the explanation of the radiation patterns. The electric field distributions of these resonant modes are then simulated and the corresponding radiation patterns are investigated at 3.8, 4.8, and 9.5GHz, as shown in Figs. 4.12–4.14, respectively. Fig. 4.12 shows the first resonant mode at 3.38 GHz, where the electric fields are concentrated at the upper center part with polarization mainly in the y-axis. This set of field distribution is locally similar to that of mode in a rectangular waveguide [46], and considered as the fundamental mode of the antenna. The radiation pattern of this mode is like a small dipole oriented in the y-axis.
leading to a bidirectional pattern in the E-plane (yz plane) and omni directional pattern in the H-plane (xz plane), as shown in Fig. 4.15(b).

Fig. 4.12 Distribution of electric fields at first resonant mode at 3.38GHz
(L₁=26mm, L₂=22.65mm, L₃=9mm, L₄=10.85mm, L₅=7mm, S=2mm, W=3mm, h=1.6mm, εᵣ=4.4 and G=0.35mm)

Fig. 4.13 shows the second resonant mode at 4.8 GHz where both x- and y-component fields exist. Note that the x-component fields of the left and right sides of the stub are in the opposite directions that cancel out each other at far fields in the symmetric E-plane. Therefore, the E-plane patterns are almost unchanged and still have good polarization isolation (x-polarized level better than 20 dB), as shown in Fig. 4.15(c). However, the x-component fields generate cross-polarized patterns in the H-plane, as shown in figure.
Fig. 4.13 Distribution of electric fields at second resonant mode at 4.8GHz
\( (L_1=26\text{mm}, L_2=22.65\text{mm}, L=9\text{mm}, L_3=10.85\text{mm}, L_4=7\text{mm}, S=2\text{mm}, W=3\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4 \text{ and } G=0.35\text{mm}) \)

Fig. 4.14 shows the third resonant mode at 9.5 GHz, where the y-component fields are partially shifted to lower part and concentrated to the left and right sides of the CPW feed. This field distribution contains multiple higher order modes and makes the peak of E-plane patterns shift slightly from the z-axis, as shown in Fig. 4.15(d).

Fig. 4.14. Distribution of electric fields at third resonant mode at 9.5 GHz
\( (L_1=26\text{mm}, L_2=22.65\text{mm}, L=9\text{mm}, L_3=10.85\text{mm}, L_4=7\text{mm}, S=2\text{mm} \), \( W=3\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4 \text{ and } G=0.35\text{mm}) \)
Fig. 4.15 Measured radiation pattern of the triangular slot antenna at the frequencies (a) 3.1 GHz (b) 3.38 GHz (c) 4.8 GHz (d) 9.5 GHz and (e) 10.6 GHz.

(L₁=26mm, L₂=22.65mm, L₃=9mm, L₄=10.85mm, S=2mm, W=3mm, h=1.6mm, εᵣ=4.4 and G=0.35mm)
From the measured radiation pattern of the antenna shown in Fig.4.15, it is clear that the antenna exhibits omnidirectional pattern in the higher frequencies also. This is also confirmed by the time domain measurements of the antenna discussed in section 4.4.

4.2.3.6 Design of the Triangular slot UWB Antenna

Since we are interested in the ultra wide band width, centre frequency of operating band is taken into account while deriving the design equations. The criteria for designing the antenna is as follows.

1) Design a 50Ω CPW line on a substrate with permittivity \( \varepsilon_r \). Calculate the effective permittivity of the substrate \( \varepsilon_{\text{eff}} \) using \( \varepsilon_{\text{eff}} = (\varepsilon_r + 1)/2 \).

2) Ground plane plays a major role in determining the first and second resonances. The dimensions of the ground plane are calculated as follows.

\[
L_1 = (\lambda_c) \hspace{1cm} (4.1)
\]

\[
L_4 = (0.27 \lambda_c) \hspace{1cm} (4.2)
\]

where \( \lambda_c \) is the wavelength corresponding to centre frequency of the operating band.

3) Sides of the triangle \( L_2 \) and \( L_3 \) are calculated using

\[
L_2 = (0.87 \lambda_c) \hspace{1cm} (4.3)
\]

and

\[
L_3 = (0.417 \lambda_c) \hspace{1cm} (4.4)
\]
4) Length of the rectangular stub $L$ and the gap between stub and ground plane separation $S$ are calculated using

$$S = 0.076 \frac{\lambda}{c} \quad (4.5)$$

and

$$L = 0.346 \frac{\lambda}{c} \quad (4.6)$$

In order to justify the design equations, the antenna parameters are computed for different substrates (Table 4.1) and Table 4.2 shows the computed geometric parameters of the antenna.

**Table 4.1 Antenna Description**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Antenna 1</th>
<th>Antenna 2</th>
<th>Antenna 3</th>
<th>Antenna 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminate</td>
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<td>FR4 Epoxy</td>
<td>Rogers RO3006</td>
<td>Rogers6010LM</td>
</tr>
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<td>1.6</td>
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</tr>
<tr>
<td>$G$ (mm)</td>
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<td>0.35</td>
<td>0.45</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Table 4.2 Computed Geometric Parameters of the Antenna**

<table>
<thead>
<tr>
<th>Parameter (mm)</th>
<th>Antenna 1</th>
<th>Antenna 2</th>
<th>Antenna 3</th>
<th>Antenna 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$</td>
<td>33.8</td>
<td>26</td>
<td>22.5</td>
<td>18</td>
</tr>
<tr>
<td>$L_2$</td>
<td>29.47</td>
<td>22.6</td>
<td>19.65</td>
<td>15.6</td>
</tr>
<tr>
<td>$L_3$</td>
<td>14.1</td>
<td>10.85</td>
<td>9.4</td>
<td>9</td>
</tr>
<tr>
<td>$L_4$</td>
<td>9.11</td>
<td>7</td>
<td>6</td>
<td>4.85</td>
</tr>
<tr>
<td>$S$</td>
<td>2.6</td>
<td>2</td>
<td>1.735</td>
<td>1.36</td>
</tr>
<tr>
<td>$L$</td>
<td>11.71</td>
<td>9</td>
<td>7.8</td>
<td>6.22</td>
</tr>
</tbody>
</table>
Fig 4.16 shows the reflection coefficients of different antennas as given in Table 4.2. In all the cases antenna is operating in the UWB region.

4.2.3.7 Current distribution and radiation pattern of the triangular slot UWB antenna

The $|S_{11}|$ can only depict the performance of an antenna as a lumped load at the end of the feeding line. The elaborated electromagnetic behaviour of the antenna can only be revealed by examining the current distributions or radiation patterns. The typical current distributions of the antenna at the resonant frequencies and the corresponding radiation patterns are displayed in Fig. 4.17. From the current distribution, it is clear that both first and second resonances are produced by the symmetrical path ABC and DEC. Third resonance corresponds to a $\lambda g /4$ variation along the path FG. Compared to ground
modified monopole and serrated monopole antennas, the antenna exhibits near omni-directional pattern in the entire UWB spectrum.

Fig. 4.17 Simulated surface current distribution and radiation patterns of the triangular slot antenna at (a) 3.38GHz (b) 4.78GHz and (c) 9.6GHz 
\((L_1=26\text{mm}, L_2=22.65\text{mm}, L=9\text{mm}, L_3=10.85\text{mm}, L_4=7\text{mm}, S=2\text{mm}, W=3\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4\text{ and } G=0.35\text{mm})\)
4.2.3.8 Gain and Efficiency of the triangular slot UWB antenna.

The gain and efficiency are two important figure of merit of the antenna. The gain of the antenna is measured using gain comparison method while the efficiency of the proposed antenna is measured using Wheeler cap method. The measured gain and efficiency of the antenna are depicted in Fig.4.18. A peak gain of 5.5dBi is observed at 11GHz and it is also worth to note that the antenna provides almost uniform gain throughout the band. Average efficiency of the antenna is found to be 72%.

![Gain and efficiency of the triangular slot UWB antenna](image)

4.3 5.8GHz Band Notched Triangular Slot Antenna

In the proposed antenna, to avoid interference with electronic systems operating in the IEEE802.11a and HIPERLAN/2 bands, a band reject mechanism is achieved by incorporating two open ended slits as shown in
Fig. 4.19 are made at the top edge of the T stub, where the effective length of each slit is around quarter wavelength for the 5.8 GHz resonance. Dimensions of the triangular slot antenna remain same as in Fig. 4.7.

**Fig. 4.19. Geometry of the band notched triangular slot antenna**

$(L_1=26\text{mm}, L_2=22.65\text{mm}, L_3=10.85\text{mm}, L_4=7\text{mm}, S=2\text{mm}, W=3\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, G=0.35\text{mm}, L_s=2.25\text{mm}, L_g=3.5\text{mm}, D=1.5\text{mm}, t=0.5\text{mm} \text{ and } R=0.5\text{mm})$

(a) Top View (b) Side View

4.3.1 Reflection characteristics of Band Notched Triangular Slot Antenna

Fig. 4.20 plots the measured and simulated reflection coefficient of the UWB slot antenna with the narrow slit inscribed. It shows good rejection at 5.8GHz. A notch band from 5GHz to 6.1GHz is obtained.
Fig.4.20. Measured and Simulated reflection coefficient of the band notched triangular slot antenna

\[(L_1=26\text{mm},\ L_2=22.65\text{mm},\ L_3=10.85\text{mm},\ L_4=7\text{mm},\ S=2\text{mm},\ W=3\text{mm}, h=1.6\text{mm}, \varepsilon_r=4.4, G=0.35\text{mm}, L_5=2.25\text{mm}, L_6=3.5\text{mm},\]
\[D=1.5\text{mm}, t=0.5\text{mm and } R=0.5\text{mm}).\]

To design the open ended slits for band notch, the equation to be followed is

\[L_5 + L_6 + D = \frac{\lambda_{g,5.8}}{4} \quad \text{------------------------------------------------------------ (4.7)}\]

where \(\lambda_{g,5.8}\) is the guide wavelength computed at 5.8 GHz. The optimum values for these parameters are, \(L_5 = 6.45\text{mm},\ L_6 = 0.9\text{mm},\ R=0.5\text{mm}\ D = 0.25\text{mm}\) and \(t=0.5\text{mm}.

The slits function as shorted transmission lines having an electrical length of approximately \(\lambda_g/4\) at 5.8 GHz, giving a high input impedance.

The band-notched property is also observed in Fig.4.21, where the simulated 3D radiation patterns plotted at 3.38GHz, 6.0GHz, and 9.6GHz remains similar to the corresponding plots of the triangular slot antenna(Fig.4.6), without the slit except for the notched frequency at 5.8GHz. At 5.8GHz, a distinct reduction in radiation is noted for all directions.
Fig. 4.21(e) shows that the surface current distribution appears stronger around the slit at the notched frequency of 5.8GHz. This leads to destructive interference of the excited surface currents in the patch.
Measured gain and efficiency of the band notched triangular slot antenna is plotted in Fig.4.22. An average gain of 3dBi is noted throughout the operating band except at the notched frequency where a gain of -6dBi is obtained. The antenna designed has a radiation efficiency of more than 70% in the pass band and a reduction in the rejected band.

![Fig.4.22. Measured gain and efficiency of the band notched triangular slot UWB antenna](image)

The measured radiation patterns in the YZ and XZ planes of the antenna at the notched frequency are plotted in Fig.4.23. The pattern at 5.8GHz has been normalized w.r.t that at 3.4GHz. We can observe a reduction in gain by 10dB along all directions.
4.4 Time Domain Analysis of Triangular Slot UWB Antennas

In the previous sessions we have analyzed the frequency domain parameters of triangular slot and band notched triangular slot antennas. Since time domain analysis is also important for UWB antennas as frequency domain analysis, the following section describes the time domain analysis of the above mentioned UWB antennas.

4.4.1 Group delay of Triangular Slot UWB Antennas

Group delays of the triangular slot and band notched slot antennas are measured for the face to face and side by side orientations and are shown in Fig.4.24. In the case of triangular slot antenna, group delay variations are less than 1nS for both the orientations. In the case of band notched antenna, a sudden decrease in group delay is observed at the notch frequency.
4.4.2 Transfer functions of Triangular Slot UWB Antennas

In UWB application, to minimize the potential interferences between the UWB system and the narrowband systems, the variations of the transfer function magnitude and the group delay should be as acute as possible in the notch-bands and need to be constant in the un-notched bands. A transmitting/receiving antenna system satisfying these requirements will suppress the interferences coming from the narrowband systems and lead little distortion on useful signals.

Transfer functions of both antennas are measured as given in chapter 2 and are shown in Fig.4.25. It is found that transfer functions of triangular slot antenna remains almost constant in the entire operating band. But, in the case of band notched antenna, a sudden decrease in transfer function is obtained at the notch frequency.
Fig. 4.25. Measured transfer functions of (a) triangular slot UWB antenna and (b) Band notched triangular slot UWB antenna.
4.4.3 Impulse Responses of Triangular Slot UWB Antennas

Impulse responses are calculated from the measured transfer functions for various orientations of the receiving antennas and are plotted in Fig. 4.26. In the case of band notched antenna ringing is more than the antenna without band notch.

Fig. 4.26. Measured impulse responses of (a) Triangular slot UWB antenna and (b) Band notched triangular slot UWB antenna
4.4.4 Received signal waveforms of Triangular Slot UWB Antennas

For a UWB system, as shown in figure 2.2, the received signal is required to match the source pulse with minimum distortions because the signal is the carrier of useful information. The received waveform is determined by both the source pulse and the system transfer function which has already considered the effects from the entire system including the transmitting and receiving antennas.

Received pulses are plotted for triangular slot and band notch antennas by convoluting input pulses and the impulse responses in Fig.4.27. In the case of triangular slot antenna, received waveforms for the two scenarios, i.e. face to face and side by side, match with each other very well, which corresponds to the omnidirectional radiation patterns of the antenna. The signal waveform generally follow the shape of the source pulse and only have slight distortion. But in the case of band notched antenna, slight ringing is observed for the received pulses. Measurements indicate that very little distortion was introduced by the antennas and the antennas practically did not affect the transmitted pulses in a destructive way.
4.4.5 Fidelity of Triangular Slot UWB Antennas

Fidelities of the antennas are measured as explained in section 2.2 and are shown in Fig.4.28. Maximum fidelity for triangular slot antenna is found to be 97.4%. And for band notched antenna maximum fidelity is found to be 94.61%. Thus triangular slot antenna exhibits maximum fidelity to other antennas discussed in this thesis.
4.4.6 EIRP of Triangular Slot UWB Antennas

According to FCC regulations, UWB systems must comply with stringent EIRP limits in the frequency band of operation. EIRP is the amount of power that would have to be emitted by an isotropic antenna to produce the peak power density of the antenna under test. Measured EIRPs of triangular slot antennas are shown in Fig.4.29. It is clear from the figure that EIRPs of the antennas satisfies both the indoor and outdoor masks of FCC.
Fig. 4.29 Measured EIRPs of (a) triangular slot UWB antenna and (b) Band notched triangular slot UWB antenna

Photographs of the triangular slot antennas are shown in Fig. 4.30.

Fig. 4.30. Photographs of (a) Triangular slot antenna (b) Band notched triangular slot antenna
4.5 Chapter Summary

Design of a compact ultra wideband triangular slot antenna operating from 3.1 to 11.1GHz is presented in this chapter. The antenna has simple structure and nearly omni directional radiation pattern. It is very interesting to note that this antenna has only 26x26mm² in size and fed by a CPW.

The antenna appears to be an ideal candidate for the 3.1 to 10.6GHz UWB operation from the frequency domain studies. Since the antenna operates over a multi-octave bandwidth, it would be excellent to transmit pulses of the order of nanosecond duration with minimal distortion.

In the last section of this chapter, the designed UWB antenna is adapted to coexist with 5.8GHz WLAN band with minimum interference. A thin half wavelength open ended slit is inscribed on the rectangular patch to filter out the 5.8GHz WLAN band with minimum interference. The time domain performance of these antennas for validating their suitability for pulsed applications is also carried out at the end of the chapter.

References


Planar Triangular Slot Ultra Wideband Antenna


\[\text{....EOC...}\]