# Chapter 2

# Literature Review

## 2.1 Introduction

The FCC released the report and order in February 2002 about the commercial use of ultra-wide spectrum [1]. UWB antenna can be used for short range wireless communication, provided that there is no interference from other systems in the UWB spectrum. Wireless devices and systems based on UWB radio technology support low output power and high data rate (110 - 200 Mb/s) for indoor applications over a distance of 4 - 10 meters [2], [3]. This feature of the UWB has presented an opportunity and challenge for antenna designers to work in the unlicensed UWB spectrum bandwidth of 7.5 GHz (3.1 GHz–10.6 GHz). The design and investigation of various characteristics of UWB antennas has provided research opportunities to academic communities as well as the researchers associated with wireless telecommunication industries in the recent years. Considering the scope of the UWB antennas, it is necessary that the designed antenna have qualities such as small size, conformal, low cost, ease of integration, large bandwidth and high gain. Along with these features, multiband operation over the UWB spectrum is an important one [4]. The UWB spectrum possesses potential interference of existing narrow band applications. To ensure success of the UWB antennas, it is important to study the literature on narrow band, wideband and UWB antenna design.

Chapter presents detailed literature survey on microstrip and CPW fed planar antennas used for narrow band, wideband and UWB applications with respect to monopole, slot, defected ground and fractal antennas. The purpose of the literature survey is to develop the foundation for the investigation of the applications of reported antennas with their operating bands and physical dimension. The related literature review has been included in the subsequent section and is organized in the following orders: Monopole, Slot, Defected Ground Structure and Fractal Antennas. Further, the literature survey also highlights the band-notch characteristics in the UWB spectrum with the capability to reject potential interferences.

## 2.2 Monopole Antennas

I. J. Bhal and P. Bhartia [5] have enumerated a detailed theory and design of various microstrip antenna configurations. They provided a design tool to antenna engineers with illustration of various basic shapes of microstrip antennas for narrow band applications. Stohr in 1968 proposed the use of a coaxial fed ellipsoidal monopole and dipole antennas [6] with very large dimension. More antennas of this type that can be manufactured were pioneered by Lalezari et al in 1989, who invented the broadband notch structure antenna [7]. Thomas et al provided better performance [8] of a compact ready to manufacture array antenna made up of planar circular dipole element. Monopole antennas with radiating element of various shapes such as triangular, hexagonal, circular, and elliptical, yield a broad bandwidth. An elliptical monopole with an ellipticity of 1.1 yields bandwidth of 1:11 for VSWR ≤ 2 [9], [10].

N.P. Agrawal et al have shown planar elliptical elements also work well as that of monopoles with broadband characteristics [11]. Girish Kumar and K. P. Ray [12] designed and discussed standard polygon shaped planar monopole antennas for wide VSWR ≤ 2 bandwidth with simple equations for the prediction of lower edge frequency. They found experimentally that the bandwidth of square, rectangular, triangular and hexagonal monopole antennas yield a lower BW than the circular and elliptical monopole. Computational electromagnetic has become the main tool in both industrial and academic research, since it allows a cheaper design process by minimizing the use of expensive and time-consuming prototypes. The algorithms used by these tools, such as finite element (FE), finite element method (FEM) [Appendix F], method of moments (MoM) and finite-difference time-domain (FDTD), to understand the electromagnetic operation of the structures was introduced by Anders Bondeson et al [13].

### 2.2.1 Antennas for Narrow Band Wireless Applications

K. Seol et al [14] investigated a 50 mm x 30 mm size multiband monopole antenna for narrow band wireless application with an I-shaped slit on the main patch and inverted U-shaped parasitic plane to provide sufficient impedance bandwidth (1700–2500 MHz; 41.1%, 4750–6300 MHz; 33.3%) for the desired bands. A dual band CPW fed rectangular ring monopole antenna was introduced by Joong Han Yoon [15] for WLAN application with impedance bandwidth of 14.48% for the 2.4-GHz band and

11.49% for the 5.2-GHz band. Chien-Yuan Pan et al [16] have shown bandwidth improvement for WLAN rectangular monopole with a microstrip feed line excitation and a trapezoid conductor-backed plane for band broadening. It was found that the size of such an antenna (56 x 48 mm) is not suitable for compact wireless devices. H. Wang et al [17] studied capacitive and inductive loading/de-loading of the compact triple-band Bluetooth and wireless local area network (WLAN) monopole antenna.

The use of two bent slots in a pentagonal radiating patch [18] was introduced by Hsien-Wen L. et al, for 802.11a and WiMAX triple band applications with a very compact size of 25 x 25 x 0.8 $mm^3$. They demonstrated that the bent slot in a patch can be efficiently used as a band stop filter to avoid the undesired interference from 2.85–2.39 GHz and 4.08–5.05 GHz. Bahadir Yildirim [19] also presented a compact, multiband, planar and low-profile wideband code division multiple access (WCDMA)/WLAN antenna printed on metalized FR4 superstrate. He has shown that the antenna operates at 1920–2170-MHz WCDMA, and 2400–2497-MHz, 5150–5350 MHz, and 5725–5825-MHz WLAN bands.

### 2.2.2 Antennas for Ultrawideband Applications

The design of an UWB microstrip patch antenna with a small coplanar capacitive feed strip was presented by Veeresh G. Kasabegoudar [20]. The proposed rectangular patch antenna provided an impedance bandwidth of nearly 50%. Robert A. Moody et al, conducted an investigation of a co-planar waveguide fed UWB pentagon-shaped planar monopole antenna on a foam substrate [21] of size 54 mm x 45 mm and claimed the -10dB impedance bandwidth of 140% and improvement in gain to the use of rectangular slots placed both on the ground plane and on the planar monopole. V. Shrivastava and Y. Ranga [22] had studied the CPW fed pentagonal monopole antenna with asymmetric side length and quarter circular shaped ground plane for UWB communication. Microstrip fed irregular pentagon monopole structured antenna [23] for UWB communication systems with overall antenna size of 44 mm x 30 mm and bandwidth from 3.1 to 12.9 GHz was presented by Mostafa A. Abdel Fattah et al.

The microstrip fed UWB antennas were reported by several researchers as summarized below. The printed circular and elliptical shaped radiating patch monopole antennas [24]-[26] fed by a microstrip line was investigated and studied for UWB operation. It was found that the performance of the antenna with respect to its frequency domain characteristics is mostly dependent on the feed gap, the width of the ground plane and the dimension of the radiating patch. The time domain transmission tests between two identical elements showed that the circular monopoles [25] offered better performance with respect to distortion less pulse transmission than their elliptically shaped counter parts. It was found that all these antennas used various substrate heights, to achieve the UWB. Both [25], [26] have shown the calculation of lower edge frequency of the UWB band with respect to major and minor axis of the elliptical patch. J. P. Zhang et al, [27] have discussed the elliptical dipole antenna design with trimmed elliptical radiation patches and microstrip-coupled feeding structure. The antenna was printed on a 0.5 mm-thick substrate of size 55 mm × 55 mm and dielectric constant of 2.64, to achieve a wide bandwidth and radiation patterns similar to those of a conventional dipole antenna. Ntsanderh C. Azenui and H. Y. D. Yang [28] studied the crescent antenna, which evolved from an elliptical patch antenna by carving a symmetrical circular hole inside. This antenna had similar radiation properties compared to that of a full elliptical antenna, with 40% reduction in area (60% of the ellipse area).

G. M. Yang [29] had obtained an UWB from 2 to 20 GHz from a multi-resonant split-ring loop as a monopole element fed by a tapered microstrip transmission line. The UWB system and various types of UWB antennas for short range communication, Radar and Imaging applications were well discussed in [30]. Nikolay Telzhensky and Yehuda Leviatan [31] had proposed a planar differential elliptical UWB antenna optimization generic algorithm for low dispersion characteristics over the relevant frequency band for high correlation between the time-domain transmitted and received signals. The optimization was based on time-domain characteristics of the antenna. K. George Thomas et al, [32] had presented a sleeved transmission line-fed rectangular planar disc monopole antenna with a very small ground plane for the impedance bandwidth ratio 18:1. The overall antenna size was 60 mm x 120 mm.

From the above literature survey it is observed that there is little work performed on the pentagonal shaped geometry antenna. The wireless narrow band and UWB antennas designed by the researchers were of large sizes, which made them difficult to accommodate and integrate with the portable handheld wireless devices, though they have the broad or FCC specified UWB bandwidth.

CPW fed monopole antennas with various shapes of the planar radiating monopole elements such as triangular, rectangular, elliptical and circular shaped patch

[33]-[36] with two notched ground planes or trapeziform ground plane were studied for UWB operation. These UWB antennas had a bandwidth ratio of more than 10:1 for VSWR ≤ 2. The average gain of these antennas was 2.5 dBi and size of each of them had a very large substrate area of more than 2500 $mm^2$. Sheng-Bing Chen et al, [37] presented a uniplanar CPW fed antenna with a rectangular tuning stub. The overall structure of the antenna appeared like a sleeve-shaped monopole. The disadvantage of this antenna was that it had a low bandwidth of 3.14 GHz with a large total area of 2500 $mm^2$.

Y. J. Ren and K. Chang et al [38] had studied the CPW fed elliptical ring antenna. The elliptical ring was electromagnetically coupled and derived from the basic ellipse shape to reduce the area of the antenna. The antenna operated for the upper UWB applications over the frequency band of 4.6 to 10.3 GHz with an average gain 4.48 dBi. A U-shaped square patch combined with two parasitic tuning stubs was fed by a CPW and studied by M. Koohestani, M. Golpour [39] for ultrawide FRB of 129% (2.76 to 12.8 GHz). The measured gain of this antenna ranged from 1.6 to 5.3 dBi.

Kun Song et al, [40] presented a flame-shaped monopole antenna with a similar slot for wideband applications. It was found that a slot of the same shape works effectively for bandwidth enhancement. The achieved VSWR < 2 bandwidth was from 2.65 GHz to 12 GHz. K. P. Ray and S. Tiwari [41] demonstrated that a hexagonal shaped monopole can be effectively used to cover wide communication channels such as GSM (900–1800 MHz), UMTS (1885–2200 MHz), WCDMA (1.92–2.17 GHz), UWB (3.1–10.6 GHz), including some bands of super high frequency for satellite and space applications (10–15 GHz) when fed at the vertex with CPW feed. It is found that the antennas reviewed above have large sizes.

### 2.2.3 Ultrawideband Antennas with Band-Notch Characteristics

K. H. Kim et al, [42] had introduced a staircase and ball shaped microstrip feed UWB planar monopole antenna for VSWR ≤ 2 bandwidth of 15 GHz, with a round shaped ground plane. The band-notched characteristic was achieved by two parasitic patches. K. H. Kim and Seong-Ook Park [43] further studied the half-ellipse-shaped radiation patch with three steps; the ellipse-shaped slot, notch in the ground, trimmed ground, and a parasitic strip to achieve similar UWB band-notch characteristics with reduction in substrate size. In both the articles they presented rejection of the 802.11a

WLAN band. By etching proper slots (such as the inverted- L, and two inverted- L) in a co-axially fed interior of the wideband antenna, a tri-band antenna or wideband antenna with two narrow frequency notches were demonstrated by Wang-Sang Lee [44].

Chong-Yu Hong [45] had shown a 5.5 GHz band stop design by embedding a pair of T-shaped stubs inside an elliptical slot in the radiating patch. The ground plane was modified with two bevels on the upper side of the ground plane, and two semicircle slots on the bottom edge of the ground plane for improvement in high frequency radiation. A microstrip-fed semi-elliptical UWB dipole antenna [46] with band-notched performance from 5.0 to 6.0 GHz to avoid interference of WLAN systems was presented by Jin-Ping Zhang et al. Same band-notch operation with H-shaped conductor-backed plane was achieved by Reza Zaker et al, [47] with a compact antenna size, which used a microstrip feed rectangular patch. A dual notch band characteristic with a microstrip fed fork shaped tuning stub was presented by Kenny Seungwoo Ryu, and Ahmed A. Kishk [48]. They have established a multiband operation with rejection of unnecessary adjacent bands.

Raha Eshtiaghi et al, [49] presented a novel hybrid design of microstrip-fed parasitic coupled monopole antenna, in which an additional inverted semi-ellipse-shaped patch is connected to the main patch to act as a filter structure, to realize a sharp rejection frequency band from 5.1 to 5.85 GHz. The concept of segmentation of the UWB with segmenting a standard shaped radiating patch was introduced by Ke Zhang et al [50]. To achieve the VSWR $\leq 2$ UWB from 2.8 GHz–13.90 GHz, beveled shaped rectangular monopole antenna structure was studied by Hui Zhao et al, [51]. Here they have shown that the lower WLAN 5.15 GHz–5.35 GHz band is notched by means of a vertical rectangular tuning stub embedded in the centre of the beveled and slotted rectangular monopole antenna. R. Movahedinia M.N. and Azarmanesh [52] have discussed the beveled shape rectangular patch for UWB operation over 9 GHz and achieved a single band-stop (5.1 GHz–6 GHz) performance using a semi-octagonal parasitic strip located around the radiating patch.

B. Rahmati and H. R. Hassani had studied the multi-notch characterized UWB monopole antenna [53]. The monopole structure was very difficult to accommodate in compact wireless devices. In 2011, a circular monopole antenna with an acceptable band-rejection characteristic was investigated by M. Yazdi and N. Komjani [54]. The rejection band created was around 5.5 GHz by means of a mushroom-like electromagnetic band-gap (EBG) structure. The antenna area was very large (1360 mm$^2$). In 2012, T. D. Nguyen et al, [55] studied the microstrip fed UWB monopole antenna with three notch band characteristic to avoid the interference of WiMAX systems (3.3–3.7) GHz, WLAN (5.15–5.825) GHz and the downlink band of satellite communication systems (7.25–7.75) GHz. The antenna used semi-elliptical radiating patch with three circular slots and one open ended rectangular slot for notch operation.

A very small microstrip fed antenna of dimension 10 mm x 17 mm was investigated in 2012 by H. Karimi et al, [56]. The monopole used an E-shaped radiating patch with two L-shaped and a T-shaped arm for wide fractional bandwidth of 130% (2.9–14) GHz. Modified L-shaped arms with variable dimensions on the E-shaped radiating patch generated only one band-stop performance, around 5.5 GHz. D. Zhou et al, [57] discussed a half-disk shaped structured monopole antenna for single band-notch structure along with UWB characteristics. The size of this antenna was 35 mm x 35 mm having a large area of more than 1200 mm$^2$. A band-notched UWB antenna proposed by Shi-Wei Qu et al, [58] composed of a rounded bottom rectangular radiating patch and rounded CPW feed ground, operated from (2.67–12) GHz. The notch band characteristic for WLAN (5.10–5.94**)** GHz was realized by a compact coplanar waveguide resonant cell (CCRC). The antenna size was 46 mm x 30 mm, which is large when compared with the requirement of today's wireless devices. The antenna was extensively investigated not only in the frequency domain but also in the time domain.

A small, lightweight, and low cost UWB antenna of 26 mm x 35 mm size, was proposed by Wen-Shan Chen and Kai-Cheng Yang [59]. The antenna consists of a planar rectangle-semicircle-rectangle shape patch, a CPW type feed, and rectangle-shaped slot printed on a FR4 substrate of dielectric constant 4.4. The antenna exhibited a single band-reject characteristic in the range (5.15–5.825) GHz. A CPW feed compact planar UWB antenna of 26 mm × 30 mm size, with both a beveled patch and ground with 3.4/5.5 GHz dual band-notched characteristics was studied by Q. X. Chu and Y. Y. Yang [60]. Two notch bands (WiMAX/WLAN) were etched by two nested C-shaped slots in the patch. The frequency notch mechanism was discussed with an equivalent circuit model based on the dual band-notched phenomenon. Stable radiation patterns and constant gain ringing around 4 dBi in the UWB band was obtained.

D. H. Bi et al, [61] presented a CPW fed staircase shape antenna of 34 mm x 25 mm size, along with dual stop-band characteristic. By using a U-slot in the feeding line, first notch-band of 800 MHz for band rejection of WLAN was achieved and another stop-band of 600 MHz was realized by implanting two vertical slits in the ground plane.

The antenna established an impedance bandwidth of 3.01–10.67 GHz for VSWR ≤ 2, except notch bands of over (3.4–4.2) GHz and (5.1–5.9) GHz. A CPW fed novel planar UWB antenna with a band-notch characteristic was reported by Fei YU and C. Wang [62]. The antenna's size was 28 mm x 30 mm. Wide impedance bandwidth of 20 GHz was achieved with three modifications in the patch and ground, first, a 90° fan angle on the upper corners of the patch was introduced, the second one was to shape the bottom of the patch into an arc, and the third modification was to remove a small fan angle on each side of the ground plane near the feeding line. The authors have shown that implementation of a notch band between 5 to 6 GHz is similar as in [55]. A triple band-notched CPW fed compact antenna (19 mm x 24 mm) was presented by D. T. Nguyen et al, [63]. The antenna used three open-ended quarter-wavelength slots to create triple band-notched characteristics in (3.3–3.7) GHz for WiMAX, (5.15–5.825) GHz for WLAN, and (7.25–7.75) GHz for downlink of X-band satellite communication systems, respectively across a wide bandwidth from 2.45 GHz to 10.65 GHz. The antenna operation was discussed with surface current distribution to understand the effect of slots etched in the radiating patch. The antenna showed good omnidirectional radiation patterns in the pass band.

From the above literature survey, it is found that many researchers have reported and established the UWB antenna with band-notch characteristics. It is observed that the size of most of the antenna is large, the radiating patch is partially elliptical and beveled rectangular in shape with round ground plane. The analysis of an UWB antenna with an equivalent circuit [64] is rarely discussed.

## 2.3 Slot Antennas

The details about UWB technology and the design of various types of UWB antenna were presented experimentally [65]. Number of slot antenna configurations with wideband [76]-[91] and band-notch [92]-[100] operations are studied.

### 2.3.1 Slot Antennas for Narrow Band Wireless Applications

A CPW fed G-shaped antenna with a rectangular slot of 45 mm x 36 mm size was presented by Sunghun Kim et al, for WLAN applications [66]. The reduction in antenna size and broad bandwidth was achieved with a CPW feed and two folded monopoles shaped similar to the letter G. The antenna had two bands with FRB of 41.98% (2.07 to 3.17) GHz and 56.82% (4.53 to 8.125) GHz respectively. M. T. Torres and J. G. Vera-Dimas reported an antenna design of dual pentagonal slot [64] for Wi-Fi applications with 47 mm x 49 mm dimensions. The authors have illustrated testing of the antenna on a router with wireless connectivity. Dual band CPW feed antenna of 70 mm x 70 mm size was proposed by M. J. Chiang et al, for 802.11a/b WLAN applications [68]. The proposed feeding structure achieved input impedance matching over the dual-band, exhibiting two wide operating bands of the bandwidth 30.8% and 24.0%, respectively. Due to the modification in the angle of the arc-shaped tuning stub, the first-higher order resonant mode shifts to the lower frequency band to combine with the fundamental mode of the annular slot, achieving a broadband operation with the bandwidth of 3048 MHz (78.4%). The miniaturized design, with embedding in a protruded strip from the ground plane into a slit, shifts the center frequencies of two resonant bands from 2752 to 1738 MHz (size reductions of 60%) and 5022 to 3760 MHz (size reductions of 44%) respectively.

Wei Hu et al studied triple band antenna for WLAN/WiMAX applications [69]. The designed antenna is composed of a square slot, a pair of L-strips, and a monopole radiator. Experimental results demonstrated impedance bandwidths of 480 MHz (2.34–2.82) GHz, 900 MHz (3.16–4.06) GHz, and 680 MHz (4.69–5.37) GHz, can cover both WLAN in the 2.4/5.2-GHz bands and WiMAX in the 2.5/3.5-GHz bands. The current distribution analysis was presented for understanding the antenna operation. A new configuration of coaxially fed multiband / UWB antenna was introduced by Hala Elsadek et al. The antenna design consists of a V-shaped patch with unequal arms coupled electromagnetically to a single feed isosceles triangular PIFA through two unequal slots [70]. The six multiband operations were achieved by the different lengths and widths of the V-shaped patch as well as the two coupling slots. By folding the shorting wall of the triangular PIFA, UWB operation with 53% bandwidth was generated.

A rectangular slot antenna of large dimension 53.7 mm x 53.7 mm was presented by J. Y. Sze, and K. L. Wong for bandwidth enhancement [71]. The antenna was composed of 50 Ω microstrip feed with a fork-like tuning stub. Experimental results indicated that a 1:1.5 VSWR bandwidth of 1 GHz was achieved at operating frequencies around 2 GHz. A CPW fed wide rectangular slot antenna of large dimension 44 mm x 72 mm for wideband operation was discussed by H. D. Chen [72]. The impedance matching for the proposed antenna strongly depends on the location of the tuning stub in the square slot, and the impedance bandwidth was mainly determined by the width and length of the tuning stub. The impedance bandwidth of the antenna was found to be 1320 MHz (1560–2880) MHz or about 60% with respect to the center frequency at 2220 MHz.

J. Y. Chiou [73] proposed and studied a novel broadband design of a CPW fed square slot antenna loaded with conducting strips. The impedance matching was achieved by tuning the lengths of the CPW signal strip in the slot and the metallic strips. A large bandwidth of about 1 GHz (1536–2500) MHz or about 50% referenced to the center frequency at about 2.0 GHz was obtained. The proposed antenna had a peak gain of about 5.8 dBi. The disadvantage of this antenna was its large size of 70 mm x 70 mm. J. Y. Jan and J. W. Su proposed a printed wide-slot antenna fed by a microstrip line with a rotated slot for bandwidth enhancement [74]. The dimension of the antenna was 70 mm x 70 mm. A rotated slot (treated as DGS) 24.7 x 24.7 mm in size was excited by a microstrip line. The printed wide-slot antenna showed a wide -10 dB return-loss impedance bandwidth of about 2.2 GHz (3400–5600) MHz with operating frequencies of around 4.5 GHz. Over wide impedance bandwidth, the gain variation is less than 2 dBi.

A printed wide-slot antenna with a parasitic patch for bandwidth enhancement was proposed and experimentally investigated by Y. Sung [75]. The dimension of the antenna was 37 mm x 37 mm. A parasitic patch was embedded into the center of the rotated square slot, to decrease the lower resonant frequency and to increase the higher resonant frequency to achieve a wide impedance bandwidth from 2.23 GHz to 5.35 GHz. The designed antenna was suitable for the 2.4/5.2-GHz WLAN application.

### 2.3.2 Slot Antennas for UWB Application

A. Dastranj, et al [76] proposed a novel printed wide slot antenna, fed by a microstrip line, for wideband communication. The antenna was composed of an E-shaped radiating patch and a similar shaped slot in the ground plane as the DGS. The dimension of the antenna was 85 mm x 85 mm. The designed antenna had a wide operating bandwidth of 120% (2.8–11.4) GHz for $S_{11} \leq -10$ dB. A comprehensive parametric study was carried out to understand the effects of various dimensional parameters and to optimize the performance of the designed antenna. A. Dastranj and H. Abiri modified the antenna to achieve very wide impedance bandwidth by rounding every corner of radiating and E-shaped slot (DGS), with microstrip and CPW feeds [77]. The microstrip and CPW feed gave 136% (2.85–15.12) GHz and 146% (2.83–18.2) GHz, impedance bandwidth respectively.

Rezaul Azim et al presented a tapered shaped slot and rectangular tuning stub UWB antenna, printed on a FR4 substrate [78]. The FRB of the antenna was 115.5% (3–11.2) GHz. They compared the various tuning stubs shapes as well as the slots. The antenna reported a maximum gain 5.4 dBi. Shi Cheng et al, presented an UWB printed wide slot antenna using microstrip fed cone shaped radiating patch with a similar shaped slot in the ground plane, 60 mm x 60 mm in size [79]. The impedance bandwidth ratio of this antenna was 13:1 (2.2–30) GHz. In the H-plane the antenna radiates in omni direction at a high frequency. The drawback of this antenna was that it cannot be accommodated in wireless handheld devices because of its large size.

A wide bandwidth of 110% (2.79–9.48) GHz was achieved by using a CPW fed U-shaped tuning stub and a wide rectangular aperture [80]. The antenna was very large (100 mm x 100 mm) in size. The CPW and microstrip feeds for a half disk antenna structure were compared by Taeyoung Yang and W. A. Davis [81]. The antenna operated over a 3.l GHz–10.6 GHz frequency range with a low VSWR. This small antenna covers the indoor/outdoor handheld UWB application frequency range with a good impedance match and a linear phase response. A. A. Eldek et al presented a CPW fed rectangular slot antenna tuned by a patch stub [82]. They demonstrated that the antenna would be a good candidate for a variety of radar and other applications designed for frequencies between 8 GHz–22 GHz. The antenna provided 98% impedance bandwidth.

D.C. Chang et al, [83] presented an improved design of the U-shaped stub rectangular slot antenna, with a tuning pad for impedance bandwidth enhancement. The designed antenna size was 42.8 mm x 35.3 mm. The rectangular aperture was stepped at each corner for improvement in radiation performance. The FRB of the antenna is 135.7% (2.3–12) GHz and gain changes from 2 to 6.82 dBi. CPW feed rectangular slot antennas with rectangular, U, modified U, modified fork shaped plane and round rectangular aperture with round rectangular shaped tuning stub for bandwidth enhancement were discussed by several researchers [84]-[88]. A bandwidth more than 5 GHz and covering the applications of IEEE 802.11b/g/j/a/h WLAN and WiMAX were reported [84]-[86]. The FCC defined bandwidth and UWB applications were successfully covered [87], [88]. All these antennas designed for existing wireless applications had substrate area of more than 1700 $mm^2$ and sizes more than 45 mm x 45 mm. One more design for bandwidth enhancement using rectangular slot antenna with T –shaped slot in a rectangular tuning stub was reported by Boonchai Kaewchan et al, [89]. This T –shaped antenna was useful for IEEE 802.11b/g 2.4 GHz (2.40–2.48) GHz, IEEE 802.16e 3.5 GHz (3.4–3.69) GHz, IEEE802.11j (4.90–5.091) GHz, Public Safety Frequency (4.94–4.99) GHz, IEEE 802.16a 5.2 GHz (5.13–5.35) GHz and HIPERLAN application 5.8 GHz (5.7–5.9) GHz.

Pengcheng Li et al demonstrated the UWB characteristic using a U-shaped tuning stub with the elliptical/circular slots printed on the ground plane [90]. Four antennas were discussed for UWB operations using circular and elliptical slots excited by tapered shaped microstrip and CPW feed. A multi-resonance characteristic was studied in detail with lower edge frequency determination. It was shown that these four antennas radiated nearly omnidirectional over a wide bandwidth. Another design composed of four substrate prototypes, 40 mm x 40 mm in size; made of elliptical or circular stubs that excited similar shaped slot apertures were proposed for 7.5 GHz (3.1–10.6) GHz bandwidth, by Evangelos S. et al [91]. Out of the four designs, three were fed by a CPW feed and the fourth by a microstrip line feed. All structures exhibited satisfactory UWB behaviour with impedance bandwidth beyond 175%.

### 2.3.3 Ultrawideband Slot Antennas with Band-Notch Characteristics

W. J. Lui et al presented frequency notched UWB microstrip slot antenna with a parasitic tuning stub [92]. A frequency notch band from 5.10 GHz–5.85 GHz was achieved over impedance bandwidth of 2.91 GHz–11.16 GHz. The area of the antenna was approximately 900 $mm^2$. A compact aperture area of 13 x 23 $mm^2$ was obtained with a CPW feed T-shaped tuning stub for UWB characteristics [93] by Y. C. Lin, and K. J. Hung. Discussion of the correlation between the field distribution of the antenna aperture and the radiation patterns were given. The three band-notched designs using the isolated slit, the open-end slits, and the parasitic strips were presented for the rejection of 5 GHz–6 GHz band. Current distribution for the three designs at center notch frequencies were described for understanding the notch operation.

A UWB elliptical slot antenna with two notch structures embedded with open-end slit on the tuning stub and a parasitic strip on the aperture for achieving the band-notch characteristics were proposed by C. S. Li and C. W. Chiu [94]. The notch band was designed to avoid interference from 5 GHz WLAN. The gain in the rejection band was sharply reduced to -4.03 dBi. A CPW fed UWB antenna printed on FR4 substrate, 26 mm x 29 mm in size comprises a monopole-like slot and a CPW fork shaped feeding structure [95]. This proposed antenna by X. Qing and Z. N. Chen showed good impedance matching, consistent gain, stable radiation patterns and consistent group delay over an operating bandwidth of 2.7 GHz–12.4 GHz (128.5%). Band notched characteristic in the band of 5 GHz–6 GHz was achieved by adding two more grounded open circuited stubs.

A CPW feed UWB antenna with periodic open end stubs (POES) inserted in the inside edge of the rectangular aperture, trapezoidal shaped tuning stub and compact aperture area of 12 x 23 $mm^2$ was investigated by M. Naser-Moghadasi et al, [96]. Three designs of the notch filter such as slot embedded on the patch, ground and conductor-backed plane structure were implemented to reject WLAN interfering signals between 5 GHz and 6 GHz. A CPW-fed UWB antenna with a band-notch characteristic was presented by Y. S. Li [97]. Two inverted L-shaped slots in the CPW ground were used to broaden the operating impedance bandwidth (2.38–10.6) GHz as well as notch bandwidth. The notch band characteristic was realized by a tuning stub inserted in the middle of the fork like patch, with a compact size of 21 x 28 $mm^2$, and had an impedance bandwidth ranging from 2.38 GHz to 10.6 GHz for a VSWR ≤ 2, while rejecting the 5 GHz–6 GHz band.

The UWB antenna proposed by A. Subbarao and S. Raghavan operated over a band between 3.1 GHz–11 GHz for a return loss of less than -10 dB [98]. A simple C shaped slot at the bottom of a pot shaped radiating patch was printed to avoid interference with WLAN and HIPERLAN/2 (5.1- 5.85 GHz). The group delay of the antenna is less than 1 ns in the operating bandwidth except in the notched band. A UWB slot antenna, covering 3.1 GHz–11 GHz, with an octagon shaped slot and fed by a rectangular patch with a bevelled bottom edge was presented by Mohammad Mehdi [99]. A novel technique to add an extra Bluetooth band and dual notch bands (5 GHz WiMAX and 5.8 GHz WLAN) simultaneously to a compact UWB printed slot antenna was investigated. To improve the impedance matching, a stepped stub structure with CPW feed technique was proposed by A. C. Shagar and R. S. D. Wahidabanu [100]. The physical dimension of the antenna was 32 mm x 29 mm. The antenna operated across the UWB bandwidth of 1 GHz–11.6 GHz for VSWR ≤ 2, which also covered the 802.11b WLAN band. The band-notch function from 5.1 GHz to 5.9 GHz was illustrated using a staircase shaped slot inserted at the center of the radiating patch.

From the above survey, it is found that several researchers have designed the UWB slot antennas with band-notch characteristics at 5.5 GHz only. Potential interference by other bands such as WiMAX and satellite communication in UWB spectrum is not taken into account. Segmentation of the UWB band can be possible by designing band-notch characteristics at 3.5 GHz, 5.2 GHz and 7.5 GHz. By choosing a simple shape for the notch filter the antenna geometry can be made simple. These surveyed antenna are large in dimension, and will cause a problem to fit into handheld wireless devices used for indoor communication.

## 2.4 Defected Ground UWB Antennas

Many researchers have used the defected ground structure (DGS) technique to increase the electrical length of the antenna with microstrip and CPW feed for reduction in antenna size. The feed width and dimensions of the quarter wave transformer were calculated using equations given in [101]-[103].

To improve performance of the antennas with a one dimensional electromagnetic band gap, the DGS was used by Ashwini K. Arya et al, [104]. Dumbbell shaped slot in the ground plane of an antenna increases the electrical length and prevents the propagation in a particular band. They achieved size reduction of about 64% by shifting resonance frequency from 5 GHz to 1.8 GHz with a narrow bandwidth of 20 MHz. M. K. Mohamed Amin et al, [105] proposed a design of a dual rectangular ring microstrip antenna with DGS for wireless applications. The antenna was composed of a rectangular ring as a patch, microstrip feed line and DGS to improve the performance with substrate of 55 mm x 44 mm size. The antenna was designed for wireless communication such as WiFi, WiMAX, LTE and ISM band.

A double U-shaped DGS was proposed, to broaden impedance bandwidth of a microstrip-fed monopole antenna by K. H. Chiang and K. W. Tam [106]. The antenna comprised of a simple trapezoid shaped radiating patch fed by a DGS microstrip feed line to achieve broad impedance bandwidth of 1270 MHz (790–2060) MHz corresponding to FRB 112.4%. A wideband harmonic suppression microstrip patch antenna using the Koch-shaped DGS was presented by Z. W. Yu et al, [107]. The dimension of the antenna was 70 mm x 125 mm. The proposed patch antenna operated at a center frequency of 2.5 GHz and the spurious radiations up to 15 GHz were suppressed by applying the DGS below the microstrip feed line. M. Esa, et al presented and discussed cross polarization improvement in microstrip antenna by employing a DGS [108]. The antenna ground plane was defected with a V-shaped slot. They observed that with improvement in impedance bandwidth, the undesired cross polarization reduced at the three selected frequencies within the operating bandwidth. Two different slot resonators, which feature quarter-wavelength and half-wavelength configuration, as DGS were embedded into the arc shaped ground plane of the circular disk patch antennas in order to obtain the desired band-rejection of around 5.8 GHz [109]. Y. D. Dong et al showed that by choosing the quarter-wavelength slot resonator, the first spurious stop band is pushed up to three times of the center frequency of the notch and with a retention of super wide bandwidth of 15.81 GHz (1.62 GHz to 17.43 GHz). A novel printed monopole antenna (PMA) for UWB applications with variable frequency band-notch characteristic was presented by M. Ojaroudi et al [110]. The antenna configuration was made up of a stepped square radiating patch, with two U-shaped slots and a notched ground plane as DGS, with a T-shaped sleeve that provided a wide usable FRB of more than 140%. The fabricated antenna had a frequency band of 2.85 GHz to 16.73 GHz with a rejection band from 5.02 GHz–5.97 GHz. A compact CPW fed printed UWB antenna of 30 mm x 30 mm size was proposed by L. X. Li et al with pair of U-shaped DGS [111].

By adjusting the total length of the U-shaped DGS to half wavelength of notch frequency, a stop band was achieved to reject the 5 GHz–6 GHz band. The authors had confirmed the obtained results with electromagnetic software named CST and HFSS [112], [113]. Recently the researchers have started to design a notch band over the UWB spectrum with the use of embedding DGS. Tamasi Moyra et al, proposed a new DGS consisting of two square ring slots connected to a rectangular ring slot by two thin transverse slots under a microstrip line, like a modified Pi shaped microstrip DGS [114]. The stop band was tuned by varying the length and width of transverse slots. This approach led to circuit size reduction. Better transition sharpness, lower pass band insertion loss and broader stop band were observed compared to dumbbell DGS.

A unique UWB band pass filter (BPF) composed of seven DGSs positioned under the input and output microstrip line and coupled double step impedance resonator (CDSIR) were proposed for improved upper stop band performance by J. K. Lee and Y. S. Kim [115]. By using CDSIR and open loop defected ground structure (OLDGS), UWB BPF characteristics was realized and by using the conventional DGSs under the input and output microstrip line, an improved upper stop band performance was achieved. The insertion loss of the compact UWB BPF was less than 1 dB at frequencies from 4.4 GHz to 9.3 GHz. A wide upper-stop band with the insertion loss higher than 30 dB in the range of 11.1 GHz to 20 GHz was achieved with group delay less than 0.4 ns.

C. B. Guan and Z. H. Zhang presented a UWB antenna of 50 mm x 52 mm dimension, loaded with DGS [116]. The antenna was composed of microstrip line fed circle radiation patch. The DGS structure was introduced in the ground plane and under the feed line. A notch band from 7 GHz to 8.5 GHz was achieved using hair pin shaped DGS. Jangyeol Kim et al investigated a new type of antenna having a complementary split ring resonator (CSRR) and matching slot on the ground plane as the DGS [117]. The antenna was composed of a microstrip fed elliptical shaped monopole radiating patch and two complementary split ring resonator structures with substrate 36 mm x 60 mm in size. CSRR was used for rejecting the 5 GHz WLAN band (5.15–5.35 and 5.725–5.825) GHz. The CSRR's length was varied to adjust easily the notch frequency.

A compact band-notch UWB printed monopole antenna using a DGS was proposed by M. Abdollahvand et al, [118]. The band-notch characteristic was realized by adding U shaped DGS or a slit in the ground plane. By inserting T-shaped stubs in the ground plane, additional resonance was excited for increase in the bandwidth up to 118% (3–11.5) GHz. The DGS rejected the potential interference of 802.11a WLAN. A compact 28 mm x 35 mm multiple notch UWB antenna using circular monopole radiating patch was proposed using inter digital defected ground structure (IDDGS) [119]. J. K. Lee and Y. S. Kim showed multi stop-band features to efficiently reject (2.10–3.80) GHz (WCDMA), (5.30–5.90) GHz (WLAN), (7.65–7.90) GHz, and (9.55–9.75) GHz. A microstrip feed rectangular radiating patch had a staircase structure placed symmetrically at the bottom and was proposed and studied by Chen Wang et al, for triple frequency band-notched functions over UWB [120]. The antenna had a pair of C-shaped slots, a U-shaped slot on the radiating patch and double I-shaped slots on the ground plane as DGS. The measured bandwidth for VSWR $< 2$ covered the frequency range of (3.1–10.6) GHz except in (3.26–3.82, 5.06–6.23, and 7.06–7.96) GHz. The three notch-bands at 3.5/5.5/7.2 GHz were realized to avoid interference of 802.11a/b WLAN and WiMAX communication system. The peak gain reported by the antenna was 4dBi. The UWB antenna designed by A. Elboushi et al [121], composed of elliptical defected ground plane and two radiating element fed by a 50 $\Omega$ microstrip line. A circular and crescent shaped radiator was used to achieve wide impedance bandwidth of 11 GHz (3–14) GHz. The band-notch of 1 GHz (5–6) GHz was realized by making the ground plane defective with a C shaped slot in the feed line.

The proposed antenna by Nouri and G. R. Dadashzadeh consisted of a DGS and an arc-shaped step radiating patch, which was notched by removing two squares at the bottom for UWB and filtering characteristic [122]. This antenna gave a wide impedance bandwidth of 3.1 GHz–14 GHz. A modified shovel-shaped DGS was used to reject frequency notch-band operating from 5.13 GHz–6.1 GHz for Dedicated Short-Range Communication (DSRC) systems and WLAN.

## 2.5 Ultrawideband Fractal Antennas

Multi functionality with miniaturized characteristics is the need of today's wireless communication. The concept of fractal geometry was first introduced in 1975 by Benoit Mandelbrot. Since then, considerable research has been carried out in the application of fractals to achieve wide bandwidth, thereby opposing the use of antenna arrays, which take a lot of space and are bulky as compared to fractal microstrip antennas [123]. The fractal antennas are based on self-similarity and space filling properties and the original geometry is scaled down by the desired factors. These unique features of fractal geometry are used for multiband and wideband applications. Sierpinski gasket is a deterministic fractal based on self-similar property. The construction algorithm for the Sierpinski gasket using an equilateral triangle base geometry was given in [124] step wise. The space filling property led to curves that were electrically very long, but fit into a compact physical space. This second property of fractals is also known as 'Infinite Perimeter'. The fractals bring probability of multiplying self similar shapes infinitesimal times and thereby stretch the perimeter infinitely. However, in practice there is a physical limit to the increase in the number of iterations. Because of its potency, this characteristic is called as the 'Infinite Perimeter' [124, 125]. 'Space Filling Curves' is a method of achieving 'infinite' perimeter. One of the examples of space filling curves is Koch Curve, which multiplies the perimeter many times [125].

Steven Best studied and tested multiband behaviour of the Sierpinski Gasket Antenna [126]. He presented a comparison of the multiband behaviour of Sierpinski Gasket and several modified gaskets. The major portions of the Sierpinski Gasket's self-similar fractal gap structure were eliminated completely without affecting the multiband behaviour characteristics. It was demonstrated that the periodic gap structures located along the central axis of the Sierpinski Gasket determined its multiband behaviour. The comparison of the resonant properties of small space-filled fractal antennas were presented in [127]. Using a pentagonal shaped basic geometry and taking three iterations, a multiband fractal antenna was presented by Philip W. Tang [128] with Iterated Function System (IFS) coefficients for the pentagonal and hexagonal fractals.

A broadband planar Sierpinski fractal antenna for multiband application was proposed, designed, and tested by K. C. Hwang [129]. The perturbed Sierpinski fractal patch and slotted ground plane were employed to achieve broadband characteristics with a total antenna dimension of 100 mm x 53.7 mm. The achieved multiband had bandwidths of 808 MHz -1008 MHz (22%) and 1581 MHz–2760 MHz (54.3%), to cover the GSM/DCS/PCS/IMT- 2000/ISM/satellite DMB bands. The Sierpinski fractal antenna was studied by C. P. Baliarda et al, for prediction of behaviour of the Sierpinski fractal antenna, when the flare angle is modified [130].

Nima Bayatmaku et al proposed and experimented novel compact multiband E-shape fractal printed patch antenna [131]. Due to the E-shape, size reduction was achieved with enhancement in a number of operating bands. The proposed E-shape fractal antenna resonated at 945, 1945, and 2470 MHz with wide bandwidths of 250 MHz, (820–1070 MHz, 26%), 400 MHz, (1750–2150 MHz, 20% ), and 260 MHz, (2340–2600 MHz, 10%) to cover GSM-850/900, GSM-1800/1900/UMTS, and LTE-2300/2500, respectively. The design of the multiband antenna using a ring fractal for mobile communication was presented by Pourahmadazar et al, [132]. Two CPW-fed printed fractal monopole antennas were investigated by Y. C. Lee et al, for wideband applications [133]. They showed that the feed and the fractal created a strong effect on the antenna's impedance bandwidth and radiation patterns. The antenna was printed on the FR4 substrate of 1.6 mm thickness and relative permittivity 4.4, with 58 mm × 52 mm dimension. They analyzed two CPW fed antennas, one composed of a circular fractal shaped monopole and the other a rectangular fractal shaped monopole. The bandwidth of rectangular fractal shape monopole antenna was found from 1.5 GHz to 13.2 GHz.

A planar monopole antenna using the Penta-Gasket-Koch (PGK) was introduced for multi applications such as ICMS, DECT, UMTS, Bluetooth, and WLAN systems [134]. The design achieved good input impedance match and linear phase of $S_{11}$ throughout the pass band of 1.5 GHz–20 GHz with 5 dB criterion for impedance bandwidth and measured gain of 4 dBi. For analyzing the time-domain characteristics, the antenna was assumed to be excited by the three wideband signals corresponding to (1.5–3, 6.0–12, and 13.5–20) GHz. This antenna can be used as multiband antenna in time domain applications. The dimension of the antenna was 60 mm × 70 mm, which is large and not suitable for compact devices.

A. Azari [135] introduced a coaxial feed hexagonal fractal structure of 70 mm x 70 mm dimension with two iterations for UWB applications. Multiband characteristics of this antenna were observed with significant gain. An octagonal fractal microstrip patch antenna was designed by A. Azari [136] for its use from 10 GHz–50 GHz frequency range. This super wideband microstrip antenna with a 40 GHz bandwidth had dimensions of 60 mm x 60 mm ground plane and substrate

A different CPW fed inscribed square circular shaped fractal antenna was proposed by Rajkumar et al, for UWB applications [137]. The proposed antenna was printed on a FR4 substrate of 24 mm x 37 mm size. The achieved wide impedance bandwidth was 12 GHz (3.01 to 15.0) GHz at VSWR 2:1, which corresponds to FRB 133.149%. A wheel-shaped fractal antenna was fabricated and tested for wide impedance bandwidth from 0.95 GHz to 4.495 GHz corresponding 130.21% at $S_{11} \leq 10$ dB [138]. The fractal antenna was curved from the solid circular patch of 50 mm diameter. A size reduction of 58% was achieved and was claimed for mobile and wireless applications. A CPW feed pentagonal cut fractal antenna of 52.45 mm x 58 mm dimension was presented for wide impedance bandwidth from 2.5 GHz to 15 GHz with a minimum backscattering [139]. A CPW fed wide slot UWB antenna with notch band characteristic was presented numerically and experimentally. The antenna composed of cantor set fractal radiation patch, tapered corners wide slot, and T-shaped tuning stub suspended at the top of the wide slot to achieve the notch band characteristic [140]. The antenna had impedance bandwidth range from 2.8 to 11 GHz for VSWR ≤ 2. The designed antenna successfully avoided the potential interference of 802.11a WLAN. Wideband E-shaped patch antennas for wireless communication was proposed by Fan Yang et al [141]. The proposed antenna incorporates two parallel slots into a microstrip patch for wide bandwidth. The wideband mechanism is explored by investigating the behaviour of currents on E shaped patch. The final proposed antenna reports a FRB of 30.3%.

## 2.6 Key Findings from Literature Survey

In the literature survey for various antennas of monopole, slot, DGS and fractal type, used for WLAN, wideband and UWB applications the following key findings are made:

1. Several researchers have developed wideband antennas operating as dual or multiband for existing wireless applications.
2. Most of the wideband and UWB antennas were designed with large dimensions, which will cause problems to fit into handheld wireless devices.
3. Multiband antennas were developed with multilayer structure and by use of fractals.
4. Many researchers have used circular, elliptical and rectangular shaped radiating patch to achieve UWB characteristics. They converted the UWB into dual band by designing a notch filter for rejection of WLAN 802.11a (5–6) GHz band. But the potential interference occurring from other bands such as satellite uplink and down link frequency, WiMAX, and DSRC etc. in UWB spectrum is not taken into account.
5. Multiple notch bands were unnecessarily designed to reject sub bands from 5 GHz–6 GHz spectrum in the same antenna configuration, when a single wide stop band can work.
6. The reported band-notch techniques, used the traditional technique of printing a C, U and T–shaped slot in the radiating patch.
7. The multiple notch bands located across the UWB spectrum for its segmentation, will be a good solution for development of multiband characteristics, which is rarely reported.
8. The inherent notch-band configurations are not adopted in the reported antenna designs for making the antenna geometry simple.
10. The researchers have rarely shown interest in pentagon geometry.
11. The reported antenna designs were moderately miniaturized in physical size for easy integration with the MMIC of UWB wireless devices.

These key findings lead to the motivation for the current research and enable the scholar to define the problem statement with research objective and expected outcomes, covered in the previous chapter. Further the literature survey also provides the foundation for the methodology to be adopted for the UWB antennas investigations and is covered in the subsequent chapters.