CHAPTER 1 INTRODUCTION

1.1 Introduction

In the recent years, the wireless communication technology has experienced an amazing growth due to the rapid advances in semiconductor research and increasing demand for high-data rate services. These high data rate demands have motivated the evolution of ultra-wideband (UWB) technology, whose origin date back to the late 19th century. UWB technology refers to the transmission and reception of ultra-short pulses over a spectrum of several GigaHertz (GHz). As a result of this huge spectral occupancy, it provides unique and attractive features of ultra-high-speed data rates, ultra-fine time resolution for precise positioning & ranging, multipath immunity and low probability of interception due to the low power spectral density. UWB systems operate at very low power. Because of these great potentials, UWB technology is being considered to be used at the physical layer of next generation short-range wireless communications, radar, ad-hoc networking, sounding and positioning systems.

The UWB technology was defined by two different agencies i.e. OSD/DARPA (Office of the Secretary of Defense, Defense Advanced Research Projects Agency) and Federal Communications Commission (FCC). According to OSD/DARPA, the term ultra-wideband refers to electromagnetic signal waveforms having -20 dB fractional bandwidth greater than 25% with respect to the center frequency or that occupy 1.5 GHz or more of spectrum. After considering the noise constraints, FCC [1] defined UWB signal as a signal whose -10 dB fractional bandwidth is larger than 20% or whose -10 dB absolute bandwidth is larger than 500 MHz. It also allocated the unlicensed spectrum from 3.1 to 10.6 GHz for UWB applications with a maximum Effective Isotropic Radiated Power (EIRP) of -41.3 dBm/MHz (74nW/MHz).

In the allocated spectrum of UWB applications, several narrow frequency bands used for commercial applications like Wi-Fi/Bluetooth (2.4-2.484 GHz), WiMAX (3.3-3.6 GHz), INSAT (4.5-4.8 GHz), lower WLAN (5.15-5.35 GHz) and higher WLAN (5.725-5.825 GHz), IEEE INSAT/super-extended C-band (6.7-7.1 GHz), X band (7.25-7.76 GHz), International Telecommunication Union (ITU) (8.01–8.55 GHz) band and the Satellite Digital Multimedia Broadcasting (S-DMB) band (2.63-2.655 GHz) are covered. This overlapping of UWB frequency spectrum and other commercial applications bands increased the demands for the design of antenna structures having band notch characteristics.

Researchers from both academics and industry investigated several antenna structures to utilize UWB technology in wireless communication systems. Among the investigated antenna structures like horn, helical, spiral, magnetic antenna, parabolic reflector dipole etc., many of them provided ultra-wideband but failed to get their application in wireless systems due to their size and three dimensional structures. For the integration of antenna structure into compact devices, UWB microstrip antenna structures proved to be the most suitable candidates. Due to the exponentially reducing dimensions of the communication devices, compact microstrip antenna having wide bandwidth is still a challenging issue for UWB antenna designers. These problems are resolved by investigating planar monopole structures, fractal structures and dipole structures.

In light of the above, it was thought useful to take up the topic on ultra-wideband antenna structure for investigations emphasizing on size miniaturization and bandwidth enhancement. Therefore, the author has made an endeavor to undertake some of the problems such as designing miniaturized monopole structures, miniaturized fractal structures and miniaturized dipole structures. Consequently simulation and experimental investigations are taken up, the entire details of which are given in the following chapters that embody the present thesis.

Before going to the actual problems, an attempt has been made to survey the available literatures on the topic and consequently, a brief historical review is presented in the following section.

1.2 Historical Review

The main root of ultra-wideband antenna was the “spark gap” technology in ancient age. In 1893, Hertz [2] conducted the first experiment on UWB by using wideband loaded dipoles to radiate sparks. However, this type of communication was abandoned at that time due to non-availability of resources to recover the wideband energy effectively.

It is followed by Lodge's [3] (1898) patent in which the concept of “syntony”, the idea of tuning transmitter and receiver to the same frequency, to maximize the received signal was introduced. In the same patent, a variety of “capacity areas’’ or antennas quite familiar to modern eyes were also discussed. Several shapes of dipoles such as spherical dipoles, square plate dipoles, biconical dipoles, and triangular or “bow-tie” dipoles were also disclosed. The concept of monopole antenna using the earth as a ground was also introduced.

For next four decades, no research took place in the field of UWB antennas. Thereafter, in 1939, Carter [4-5] improved the Lodge’s original design by incorporating a tapered feed. It was the first key step of incorporating a broadband transition between feed line and radiating elements. The biconical antenna and conical monopole with wider bandwidth were discovered, so that they could be used in television communication.

In 1940, Schelkunoff [6-7] proposed elaborated conical waveguides and feed structures in conjunction with his spherical dipole that was suggested by Carter. Unfortunately, this spherical dipole antenna does not appear to have seen much use. Perhaps, the most prominent UWB antenna of the period was Lindenblad's [8] coaxial horn element (1941). The idea of a sleeve dipole element was improved by the addition of a gradual impedance transformation for bandwidth enhancement. In fact, this coaxial element symbolized the entire television research effort [9]. After this coaxial element, Brillouin [10] explored other more traditional horn designs during this period.

King [11] (1942) and Katzin [12] (1946) also designed correspondingly conical and rectangular types of horn. In 1947, Masters [13] proposed an inverted triangular dipole with parabolic reflector. Significant advances had also been made in magnetic UWB antennas. Marie [14] in 1962 took the concept of a slot antenna and improved its bandwidth by varying the width of the slot line. More recent developments include a variety of more sophisticated electric antennas. Stohr [15] proposed the use of ellipsoidal monopoles and dipoles in 1968. In 1985, Harmuth [16] came forward with another improved magnetic antenna by introducing the concept of the large current radiator. Ideally, this magnetic antenna looked like a current sheet radiating from both sides. Antenna designers typically employ a lossy ground plane to limit undesired resonances and reflections. Due to this, the efficiency and performance of large current radiators get limited. Lalezari *et al.* [17] (in 1989) invented the broadband notch antenna. Later, Barnes [18-20] pioneered a novel UWB slot antenna in 2000. This slot antenna maintained a continuous taper. It was used in the RadarVision 1000, first generation through-wall radar of the Time Domain Corporation. With proper design of the slot taper, excellent broadband matching and performance can be obtained.

In the upcoming three sections, planar monopole, fractal and dipole antenna structures reported for UWB applications are briefly discussed.

1.2.1 Monopole Antenna

In 1992, Honda *et al.* [21] presented a monopole UWB antenna by replacing the wire monopole with a circular disc. Agrawall *et al.* [22] (1998) discovered that planar elliptical monopoles work well. Thereafter, Evan and Ammann [23] (1999) presented a formula for the dimensions of a trapezoidal monopole for a lower cutoff frequency in the range of 500 MHz to 6 GHz. In the same year, a planar square UWB monopole antenna was designed and a relation of square patch side length with the lower cutoff frequency was proposed by Ammann [24-25].

In 2003, Wang *et al.* [26] presented a coaxial probe fed UWB monopole antenna by integrating a shorted square patch with a monopole and rectangular ground plane. Daviu *et al.* [27] proposed a square planar monopole antenna with a double feed by using a modified feeding structure. Double feed degraded the polarization properties and the impedance bandwidth performance of the antenna. The bandwidth was enhanced by beveling the lower corners of the radiating patch.

In 2004, Su *et al.* [28] enhanced the bandwidth of a square monopole antenna fed by a coaxial probe by introducing rectangular notches at the lower two corners of the patch. Ammann and Chen [29] put forward a method of offsetting the feeding position from the center of the patch to enhance the bandwidth of a square monopole antenna. Due to this asymmetrical feeding, the E-plane null reduced and the H-plane patterns also got slight offsets. On the other side, Rikuta and Kohno [30] presented four configurations of UWB planar monopole antenna by using dual frequency square monopole patch. In first configuration, two rectangular patches were connected by a shorting pin while in the second configuration, the upper patch was replaced by a wire monopole. In other two configurations, two above mentioned first antenna configurations were connected orthogonally which resulted in the shifting of the lower resonance towards lower frequency as the antenna size is increased.

Liang *et al.* [31] investigated the effect of variation in the feed gap and ground plane width on the UWB performance of circular disc monopole antenna. A circular disc monopole with square ground plane and another with rectangular ground plane having narrower width were designed. Kerkhoff and Ling [32] loaded a wideband square patch antenna with an inverted U slot to introduce band-notch characteristics without degrading the wide band operation. A planar inverted cone antenna (PICA) with a perpendicular ground plane was presented by Suh *et al.* [33]. It had a radiation pattern similar to monopole disk antennas along with an impedance bandwidth of 10:1 and monopole type omnidirectional pattern over 4:1 bandwidth. The higher edge frequency of the bandwidth was increased by loading the radiating patch with two circular holes. This slot loading improved the pattern bandwidth to 7:1. Liang *et al.* [34-35] presented a microstrip line-fed printed circular disc UWB monopole antenna and carried out its time domain analysis by using the first-order Rayleigh pulse.

In 2005, on the other side, an investigation on the effect of varying the patch width, feedline width and feed gap on the impedance bandwidth of a rectangular patch antenna was presented by John and Ammann [36]. Lee *et al.* [37] designed a coaxial probe fed planar monopole antenna fed by a coaxial probe with dual band notched functions, achieved by loading the radiating patch with three U-shaped slots.

Later in 2005, a CPW-fed inverted triangular UWB monopole antenna was proposed by Liu and Kao [38]. An ultra-wideband performance was achieved by loading the rectangular ground planes with rectangular notches.

Lin *et al.* [39-40] designed a planar triangular UWB monopole antenna. They studied the effect of various source pulses (first-order Rayleigh pulses with σ of 20, 30, and 50 ps) on the radiated power density spectrum (PDS) shaping. Solis and Aguilar [41] designed an UWB antenna with wider bandwidth by beveling the lower corners of a rectangular monopole instead of a square monopole patch. Qiu *et al.* [42] enhanced the bandwidth of a square monopole antenna by applying beveling technique to all four corners of the patch symmetrically. Liang *et al.* [43] derived a circular-ring UWB monopole antenna by removing the central part of circular disc monopole antenna [35].

Later on, Padhi *et al.* [44] investigated the effect of tapered feedline on the performance of a circular disc monopole antenna and circular ring monopole antenna as compared to the circular disc monopole antenna with conventional rectangular feedline. After this, a circular ring and a square-ring with a semi-circular base antenna configuration were investigated by the same authors [45]. Su *et al.* [46] introduced single band notch characteristic in a coaxial probe fed beveled square monopole UWB antenna by loading the patch with a half-wavelength inverted U-shaped slot. This is followed by Liang *et al.*'s [47] planar tapered-CPW-fed UWB monopole antenna comprising a circular radiating patch and a trapeziform ground plane. On the other hand, Cho *et al.* [48] presented a microstrip line fed half-bowtie UWB monopole antenna with 5 GHz band-rejection filter, achieved by loading the radiating patch with U-shaped slot. The bandwidth was enhanced by using staircase-shape at the edges of half-bowtie radiating patch to excite several frequency resonances, two slits near the feedline for the impedance matching improvement and a modified ground plane structure with its both side edges constructed in circular shape to reduce the beam tilting.

In the same year, Kim *et al.* [49] designed a microstrip line fed inverse bell shaped UWB monopole antenna. A good impedance matching over a wider bandwidth is achieved by using partial ground plane with a slit. The band-notch function was realized by introducing a ring-shaped parasitic patch in the bottom layer of the substrate. Jung *et al.* [50] achieved a wider impedance bandwidth by embedding a pair of notches at the two lower corners of the microstrip line fed rectangular patch and a notch in the truncated ground plane. Kim *et al.* [51] enhanced the impedance bandwidth by utilizing the ball shape & three steps in the radiating patch to increase the effective electrical length at lower frequency and a partial ground plane. Two tilted parasitic patches gap-coupled to the radiating element were utilized to introduce band-notch function. Later, Kim *et al.* [52] designed a CPW-fed UWB monopole antenna by using Genetic Algorithm to determine the radiator shape and analyzed it by using the finite-difference time-domain (FDTD) method.

In the same year, Jung *et al.* [53] widened the bandwidth of a microstrip-fed monopole antenna by cutting two L-shaped notches and by appending two stubs to the radiating patch. The L-shaped notches improved the impedance matching at middle frequencies within the bandwidth by affecting the electromagnetic coupling between the lower edge of the rectangular patch and the truncated ground plane. The appended stubs improved impedance matching at higher frequencies. Chang *et al.* [54] investigated a CPW-fed U-shaped UWB monopole antenna with finite ground plane.

At the end of same year, Chen *et al.* [55] added two sleeves to the CPW-fed monopole to excite two resonant modes with good impedance matching to achieve a wide impedance bandwidth. Liang *et al.* [56] designed a CPW-fed circular disc UWB monopole antenna. The bandwidth was found to be very sensitive to the changes in feed gap, width of ground plane and diameter of the disc. Chung *et al.* [57] enhanced the bandwidth of a microstrip line fed UWB rectangular monopole by introducing a narrow slit on the radiator. A band notch function for 5.0-5.9 GHz was achieved by loading the patch with a tilted inverted U-shaped slot.

In 2006, Chen *et al.* [58] presented a CPW fed heart shaped UWB monopole antenna. Ray *et al.* [59] investigated two UWB monopole configurations i.e. a wire mesh of radius of a circular disc monopole (CDM) with peripheral solid copper rim and an annular ring. These configurations solved the problem of weight and wind loading associated with circular disc monopole. Lee *et al.* [60] presented eight configurations of dual band notch characteristic antenna by using multiple ∪, ∩ and inverted-L shaped slots in a coaxial probe fed monopole. Izquierdo *et al.* [61] presented a dual-layer UWB monopole antenna comprising a circular disc patch loaded with a circular notch at its upper edge and fed by a shielded strip-line. This shielding of strip line supported non-dispersive TEM mode propagation and reduced the problems of feed cross-talk and losses. Qu *et al.* [62] achieved single band notch function by embedding a compact coplanar waveguide (CPW) resonant cell (CCRC) in an UWB monopole antenna.

Gao *et al.* [63] introduced band-notch characteristics for frequency band centered at 5.55 GHz by embedding a quarter-wavelength tuning stub in the circular ring monopole. Nikolaou *et al.* [64] enhanced the bandwidth of two CPW-fed elliptical monopole UWB antennas by tapering the feed line to improve the matching between the transmission line and elliptical radiator. The WLAN band notched characteristic was introduced by loading the radiating patch with half wavelength U-shaped and C-shaped slots. Jan *et al.* [65] designed a CPW-fed monopole antenna by utilizing a two-step monopole radiator and a symmetrical four-step slope ground plane.

Eldek *et al.* [66] enhanced the impedance bandwidth of an UWB tap monopole antenna by adding the slit in one side of the monopole to excite an additional resonance, by using a tapered transition from feedline to the monopole for reduction in reflections resulting from sudden change at the feed point and two-step staircase notch in the ground plane to modify the capacitance between the patch & the ground plane. They introduced band-notch characteristics for WLAN band around 5.5 GHz by loading the radiating patch with an inverted U-slot. Same authors [67] used finite-difference time domain (FDTD) method to carry out the numerical analysis of this antenna [66].

Following it, Ray and Ranga [68] designed a modified vertex fed planar equilateral triangular monopole antenna (PETMA) by chopping off the sharp vertex of the PETMA to resolve the problem of large impedance variation between various modes and to enhance the bandwidth due to shifting of input impedance loop towards the left side closer to the centre of the Smith chart. Liang *et al.* [69] presented a CPW-fed rectangular monopole with a tapered feed and trapezoidal ground planes.

In 2007, Zhou *et al.* [70] presented a swallow-tailed UWB monopole antenna with semi-elliptical base and investigated the effect of varying the ellipticity ratio and the feeding height on the antenna performance. Zhou *et al.* [71] introduced band notch characteristics for the frequency band around 5.5 GHz in the UWB antenna [70] by loading the radiating patch with inverted U-shaped slot and inverted V-shaped slot.

Parallel to this, Ray and Ranga [72] carried out the parametric study of the planar elliptical UWB monopole antenna by varying the ellipticity ratio and modified the formula to calculate the lower edge of the bandwidth. A curve displaying the relation between the length of the feedline and the lower band edge frequency was also given. Valderas *et al.* [73] proposed an equation to find out the upper cut off frequency for a staircase-profile planar monopole antenna having N number of stairs. By using the proposed equation, four antenna configurations having staircase and tapered profile were designed.

Liu and Chen [74] proposed a fork-shaped UWB monopole antenna with band-rejection characteristics. A wider impedance bandwidth was achieved due to two symmetrical vertical strips, one on each side of the central strip. Each of the two side strips was loaded with an inverted L-shaped slot at its down corner near the centre strip. Single band-notch function was realized by extending the feed line i.e. the middle strip of the fork-shaped radiating patch. Yi *et al.* [75] designed an UWB monopole antenna by using a trident-shaped microstrip feedline having bevel on its both sides for bandwidth enhancement and cross-polarization reduction along with a square patch.

Lee and Sun [76] presented a CPW-fed tapered UWB monopole antenna comprising a semicircle shaped patch and two semicircular ground planes. The band notch function for 5.1-6.4 GHz had been introduced by modifying the U-shaped slot. Nikolaou *et al.* [77] designed a CPW-fed elliptical UWB monopole antenna with band-rejection function for WLAN band by connecting two resonating inverted L-shaped stubs to the elliptical radiator. The reconfigurable band-rejection property had been implemented by inserting reconfigurable switches like PIN diodes or MEMS between the stubs and radiator. Bae *et al.* [78] put forward a flexible UWB monopole antenna comprising a flat monopole radiator for omnidirectional pattern; stepped CPW feed line and the declined shape of the ground plane for bandwidth enhancement. The band notch function at 5 GHz was achieved by etching two slits on the radiator.

Later on, Chawanonphithak *et al.* [79] proposed a UWB bidirectional elliptical ring antenna consisting a circular monopole with curved slot for 5.8 GHz band rejection and an elliptical ring for controlling bidirectional pattern and gain improvement.

In the same year, Kerkhoff and Ling [80] investigated a square shaped UWB monopole antenna with an inverted U-shaped slot for band-rejection function. They demonstrated that the radiation pattern of a traditional band-notched planar monopole antenna were asymmetric leading to directional pattern and limiting the notched bandwidth. It was also demonstrated that the azimuth angle of peak gain changes with the frequency variation in the notched band. The quality of the band-notch antenna had been quantified by calculating the attenuation provided by the antenna relative to the original antenna without notch. A band-notched planar monopole antenna having improved azimuth plane radiation pattern symmetry was also designed by developing a GA optimizer, which used a matrix-based chromosome to describe the shape of the planar monopole element. Solis *et al.* [81] enhanced the bandwidth of a planar UWB monopole antenna by utilizing defected microstrip structure (DMS) and beveling techniques.

On the other side, Kim and Jee [82] presented a CPW-fed LI-shaped UWB planar monopole antenna comprising an L-shaped monopole and an I-shaped open stub monopole at the end of feed line. A wide impedance bandwidth was achieved by the superposition of three different current paths or resonances excited due to the L-shaped monopole and at 5.4 GHz due to I-shaped stub. Later on, Luo *et al.* [83] proposed an UWB monopole antenna with an annular coplanar waveguides feeding structure. Its bandwidth had been enhanced by introducing a ring in the feeding structure. Dual band notch functions were realized by inserting two quarter-wavelength tuning stubs into the proposed feeding ring and radiating ring, respectively.

In the same year, Su *et al.* [84] presented a U-shaped UWB monopole antenna to be used as an internal antenna in universal serial bus (USB) dongle applications. It comprised a pair of wide-ended radiating arms and a bevel-feed transition. When the antenna was mounted at the top portion of the printed circuit board (PCB), one end of the radiating arm was also short-circuited to the system ground plane.

Later, Bao and Ammann [85] enhanced the bandwidth of an UWB planar monopole antenna by introducing a slit in the ground plane of the rectangular monopole antenna. Ling *et al.* [86] designed an UWB monopole antenna by using fourth order binomial function characterized edge curve. Ray *et al.* [87] presented a printed square monopole antenna with semicircular base having an ultra-wide bandwidth ratio of 11.31:1. The semi-circular base was introduced at the bottom of square monopole to reduce the discontinuity at feed point occurring due to abrupt truncation of feed line by the straight base of square monopole.

Ma and Wu [88] designed a band-notched folded strip UWB monopole antenna consisting a forked-shape radiator and a 50 Ω microstrip feed line. The strips of fork-shaped radiator were folded back resulting in a pair of coupled lines on the radiator, which acted as parallel resonators and provided the band-rejection at WLAN bands. Chung *et al.* [89] presented a microstrip-fed UWB printed monopole antenna consisting two monopoles of the same size and a small strip bar. The length and width of the monopoles determined the first resonant frequency and the impedance bandwidth of the lower band respectively. The length of strip bar controlled the WLAN band notch characteristic.

Kim *et al.* [90] designed a CPW-fed UWB monopole antenna comprising a rectangular patch with U-slot for producing band-notch frequencies, and two-step impedance transformer with notch in semi-circular ground plane for bandwidth enhancement. The switchable band-notch operation had been achieved by inserting a PIN diode on the U-slot.

In 2008, Lin *et al.* [91] enhanced the bandwidth of conventional planar triangular monopole antenna by introducing the ridged ground planes with two symmetrically hillside-shaped corrugations for smooth transition from the feeding line to the radiating element and excitation of two additional resonant modes. Wang *et al.* [92] presented an UWB circular-ring monopole antenna with a WLAN band notch function. The band notch characteristic was obtained by inserting a circular arc slot on the ring radiator.

Yin *et al.* [93] designed a CPW-fed UWB U-type monopole antenna. It was observed that a small change in the spacing between edge of ground plane and radiator affected its impedance matching due to cancellation of its inductance by the extended reinforced capacitance resulting from the spacing between them. Same authors [94] introduced WLAN band-rejection function in above antenna structure by loading the radiating structure with a U-shaped slot. Valderas *et al.* [95] put forward three staircase profile monopoles by using the previously presented concept[73] and the angular range concept. Hu *et al.* [96] presented a meander line fed balloon shaped monopole antenna for UWB-RFID applications. Li *et al.* [97] introduced WLAN band-notch characteristics in a hexagonal planar monopole antenna by loading the radiating patch with an arc shaped slot. Ahmed and Sebak [98] designed a microstrip line fed UWB monopole antenna consisting of a half circular disc, a rectangular patch with two steps & a circular slot and partial ground plane. They achieved WLAN band-notch characteristic by loading the radiating patch with a simple and narrow arc slot.

Gayathri *et al.* [99] designed a microstrip-fed planar UWB monopole antenna comprising an inverted cone as the radiating patch and a tapered ground plane. The bandwidth had been enhanced by engraving a U-shaped section in the ground plane.

The WLAN band-notch function was realized by embedding a pair of symmetrically placed quarter wave slot resonators in the ground plane. Liu *et al.* [100] achieved dual band-notch characteristics for WiMAX and WLAN bands by etching one complementary split-ring resonator (CSRR) inside the patch.

Zaker *et al.* [101] presented a modified microstrip-fed UWB planar monopole antenna comprised of a rectangular patch with variable frequency WLAN band-notch characteristic. A wider impedance bandwidth had been achieved by loading the ground plane with two slots on both sides of the feeding line resulting in defected ground structure. The band-notch characteristics had been achieved by placing the H-shaped conductor-backed plane symmetrical to the longitudinal direction under the radiating patch. Kshetrimayum and Pillalamarri [102] enhanced the bandwidth of a planar monopole antenna by utilizing three broadband techniques i.e. modification of the circular monopole, introduction of cross-slot, and the triangular tapered microstrip feed line. Wu *et al.* [103] proposed a microstrip line fed UWB monopole having modified feeding structure composed of a trident-shaped strip & a tapered impedance transformer, ground plane and radiating patch of equal width.

Cui *et al.* [104] proposed a microstrip line-fed UWB monopole antenna comprising a rectangular monopole and a rectangular ground plane with a tapered notch. The band notch function for 5 GHz WLAN and HIPERLAN/2 frequency band was achieved by loading the radiating patch with an E-shaped slot. Yang and Sheng[105] combined the micro-genetic algorithm (MGA) and the FDTD method to design a band-notch UWB monopole antenna composed of a stepped U-type monopole loaded with an U-type slot for band notch-characteristics. Yang *et al.* [106] utilized the combination of the Jumping Genes (JG) genetic operator and the non-dominated sorting genetic algorithm II (NSGA-II) to design an UWB planar multiple-trapezoidal monopole antenna with the rectangular/rounded-corner ground plane.

Abbosh and Bialkowski [107] designed planar UWB elliptical and circular monopole antenna by using a planar conducting surface formed by the intersection of either two ellipses or two circles in a two-side conductor-coated substrate. Their complementary counter parts were also analyzed.

Wang *et al.* [108] enhanced the bandwidth of a circular monopole by loading the semi-circular ground plane with an arc shaped notch at its top edge. Zhao *et al.* [109] designed a CPW-fed UWB monopole antenna comprising a binomial function based radiator and a semi-elliptical ground plane. The band notch characteristic for WLAN band was achieved by loading the radiator with an inverted π-shaped slot.

In 2009, Elsheakh *et al.*[110] presented an UWB planar monopole antenna having a size of around 27% of the size of a conventional rectangular microstrip patch antenna and an ultra wide bandwidth with discontinuities in two frequency bands, by using a semicircular microstrip monopole radiating element with circular modified ground plane. Further improvements in the bandwidth, gain and size had been achieved by embedding metallo-EBG structure (MEBG), which removed the above mentioned discontinuities. Ahmadi and Dana [111] designed a planar pentagonal UWB monopole antenna having radiating element and ground plane of pentagonal shape with a tapered microstrip feed line. The dimensions of the radiating element and the ground plane were obtained by using the apex angle of pentagon, antenna length and substrate width. The radiating element was loaded with π-shaped or V-shaped slots to achieve band notch characteristics for WLAN band. Zaker *et al.* [112] obtained ultra-wide bandwidth by loading the ground plane with a pair of variable L-shaped slots to excite additional resonances. Single band notch characteristic for WLAN band was obtained by using inverted U-shaped parasitic structures whereas inverted fork-shaped parasitic structure was used to achieve dual band notch characteristics for WiMAX and C bands.

Karimabadi and Attari[113] designed a planar UWB elliptical monopole antenna composed of a small monopole elliptical radiating element and a modified-shape ground plane. The ultra-wide bandwidth had been achieved by removing a semielliptical part from its top edge and by introducing two narrow slits at the lower edge of the elliptical radiating element. Qing and Chen [114] presented a CPW-fed UWB monopole-like slot antenna comprising a CPW fork-shaped feeding structure to improve the effective coupling between the feeding structure and the slot. The WLAN band-notch function was achieved by adding two grounded open-circuited stubs.

Moghadasi *et al.* [115] presented an UWB planar monopole antenna with a variable band-notch frequency characteristic. It comprised a triangular-shaped antenna electromagnetically coupled to the feed microstrip-line on one side of the dielectric substrate and a triangular radiating element in the ground plane which is fed directly by the same microstrip line through a via hole. An equilateral triangular slot had been loaded into the ground plane to achieve a wider impedance bandwidth. Gopikrishna *et al.* [116] proposed a printed semi-elliptic UWB monopole slot antenna comprising a coplanar waveguide signal strip terminated with a semi-elliptic stub and a modified ground plane.

Li *et al.* [117] achieved an ultra-wide bandwidth by using a spade-shaped printed planar monopole. Three band-notch characteristics were realized by employing a hook-shaped defected ground structure (DGS) in each side of the ground plane, embedding a Ω-shaped slot on the radiating patch as well as adding a semi-octagon-shaped resonant ring on the back side of the antenna.

Thomas and Sreenivasan [118] designed a planar elliptical disc monopole antenna for universal mobile communication systems (UMTS) and ultra-wideband (UWB) dual network applications with a shaped ground plane for the stability of omnidirectional pattern. It composed of an elliptical radiating element with ellipticity>1 and a hexagonal ground plane. The radiation pattern had been improved by modifying the radiating element with symmetrical wedges cut on its sides. Ojaroudi *et al.* [119] improved the polarization properties and enhanced the impedance bandwidth of an UWB monopole antenna by using a truncated ground plane and a trapezoid slot loaded radiating patch with two tapered steps. The introduction of trapezoid slot resulted into a double fed radiating structure, having a splitted network connected to two symmetrical ports on its base. Ojaroudi *et al.* [120] achieved an ultra wide bandwidth from a printed UWB square monopole antenna by using notched ground plane with a T-shaped sleeve, which improved the electromagnetic coupling effects between the patch and the ground plane. The variable-frequency band-notch characteristics were achieved by loading the stepped square radiating patch with two U-shaped slots, which acted as half-wave resonant-structures and perturbed the resonant response. Ojaroudi *et al.* [121] introduced inverted T-shaped slot in truncated ground plane and two rectangular slots in the square radiating patch to achieve an ultrawide bandwidth.

Nikoloau *et al.* [122] designed two CPW-fed UWB elliptical monopoles with reconfigurable band rejection characteristics in the frequency band of 5-6 GHz (HIPERLAN/2 and WLAN). The band rejection characteristics had been achieved by using a $\lambda/2$ long U-shaped slot in one antenna and a pair of $\lambda/4$ long inverted L-shaped stubs placed symmetrically in second antenna, acting as resonating elements. The reconfigurability had been introduced by using the micro-electromechanical system

(MEMS) switches to activate and deactivate the resonating elements without the need of DC bias lines. Hongwei *et al.* [123] achieved band notch characteristics in a microstrip line fed square ring UWB monopole antenna by introducing a strip bar in the central slot of the patch.

Khidre *et al.* [124] enhanced the bandwidth of a rectangular microstrip antenna by introducing a slit in the ground plane and tapering the radiating patch from the feed line for better impedance matching. The reconfigurable band-notch characteristics had been introduced by adding a patch in the back plane, which acted as a half-wave resonator. Ojaroudi [125] presented a tapered band notched UWB monopole antenna. The ultra-wide band characteristics were obtained by tapering the ground plane and radiating patch. The band-notched characteristics for WLAN band were realized by embedding a folded trapezoid in an inner hole of the trapezoidal patch.

In 2010, Lizzi *et al.* [126] presented a monopole UWB antenna whose geometry is defined by a spline curve and was generated by using genetic algorithm. They introduced band notch characteristics for the first two sub-bands of the Unlicensed National Information Infrastructure (UNII) band i.e. UNII1 (5.15-5.25 GHz) and UNII2 (5*:*25-5*:*35 GHz), by loading the spline curve geometry with a U-shaped rectangular slot.

Hu *et al.* [127] developed a passive chipless UWB-radio frequency identification (UWB-RFID) localization system based on electromagnetic backscattering to transfer data from the tag to the reader. Six passive chipless UWB-RFID tags were derived from the UWB-RFID monopole [96] by replacing its microstrip line feed with a CPW feed line. Cui *et al.* [128] presented a microstrip-fed slot antenna with dual band-notched characteristics, obtained by loading the circular patch with two U-shaped slots.

Zou *et al.* [129] achieved band notch characteristics for 5.5 GHz by inserting a Z-shaped slot on the fan-shaped radiating element of a printed UWB monopole antenna. Zeng [130] designed a CPW fed UWB monopole-like slot antenna with band notch characteristics for 5-6 GHz, achieved by embedding spurlines onto the fork-shaped feeding stubs. Zeng and Zhao [131] designed a printed UWB monopole antenna by using a slit semicircular patch and a tapered coplanar waveguide (CPW). A band notch function for 4.9-5.9 GHz had been realized by loading the patch with an arc shaped slot. Zhao *et al.* [132] presented a microstrip-line fed planar UWB monopole antenna made up of a beveled and slotted rectangular patch and beveled ground plane. The WLAN band-notch characteristic was achieved by embedding a vertical tuning stub in the radiating patch.

On the other side, Fattah *et al.* [133] designed an UWB monopole antenna composed of an irregular pentagon monopole structured section with a microstrip feeding structure. Sun *et al.* [134] investigated a circular UWB monopole antenna consisting a circular radiating patch with a defected ground structure. The bandwidth had been enhanced by etching a square patch on the top side of the ground plane. Dual band notch functions were realized by loading the microstrip feedline with a U-shaped slot and the ground plane with a pair of L-shaped slots.

Zhou *et al.*[135] enhanced the bandwidth of UWB monopole antenna comprising an elliptical patch and an elliptical ground plane, by adding a small arc segment at the middle of the upper edge of the ground plane resulting into enlargement of the ground plane length and more coupling between the radiator and the ground plane. They proposed two configurations of triple band-notched UWB monopole antenna. In first configuration, the band notch functions were realized by loading the patch with split-ring slots and etching the complementary electromagnetic band gap (CEBG) at the both sides of the feed line. In another configuration, the patch was loaded with two split ring slots and a ring was etched on the ground plane. Fei *et al.*[136] proposed a CPW-fed UWB antenna comprising a finger shaped radiator. A wide impedance bandwidth was achieved due to the excitation of additional resonances overlapping with the existing resonances.

In the same year, Ma and Tsai [137] provided a solution to the problems of unsatisfactory impedance matching at both UWB low and high bands, necessity of via holes resulting in higher fabrication cost and strong fringing fields leading to nearby coupling limiting the practical applications, associated with vertically placed folded-strip resonators. The solution was consisting of placing two folded-strip resonators (interior and exterior) horizontally on the top layer of substrate, to improve the impedance matching and simplify the measurement setup due to less concentration of the fringing fields along the coupling edges of the uniplanar folded strip, with a connection between their open ends by a short line section, to provide an additional current path for improving the coupling between the adjacent resonators leading to an improvement in band rejection for 5-6 GHz.

Abdollahvand *et al.*[138] enhanced the bandwidth of a microstrip line fed rectangular monopole antenna by inserting two I-shaped notches on both sides of the microstrip feed line in the partial ground plane, which resulted into excitation of additional resonances. Two frequency bands were rejected by embedding a pair of Γ-shaped stubs in the radiation patch and a modified G-slot defected ground structure in the feeding line. Liu *et al.* [139] presented an UWB monopole antenna with band notch characteristic for the frequency band of 5.12-6.08 GHz. The band notch characteristic had been achieved by introducing a vertical coupling strip in a square slot patch.

This was followed by Eshtiaghi *et al.'s*[140] work in which the bandwidth of a microstrip line fed semi-elliptical radiating antenna is enhanced by carving two sectors at the bottom of another semi-elliptical parasitic patch, electromagnetically coupled to the main radiator. They achieved band-notch characteristic by introducing an additional inverted semi-elliptical patch, acting as a filter, connected to the radiating patch. Liu and Yang [141] presented a miniature hook-shaped UWB monopole antenna composed of a multi-branch radiator resulting into the generation of various resonant modes suitable for broadband operation.

Subsequently, Sheikhan *et al.* [142] transformed a microstrip line fed rectangular monopole antenna into an UWB monopole antenna by incorporating a ladder-shape resonant structure on its back plane. The conductor backed ladder structure was electromagnetically coupled to the radiating patch and was perturbing the monopole’s resonance responses. Sun *et al.* [143] miniaturized the size of a beveled UWB monopole antenna by removing its left half part, since the current distribution on left and right half were identical due to the excitation of an even mode by CPW-feed and the acting of the mirror symmetry as an open circuit.

Ghazi *et al.* [144] enhanced the bandwidth of a microstrip line fed square monopole antenna by loading the patch with T-shaped slots and introducing a pair of rectangular sleeve on the ground plane with a T-shaped conductor-backed plane. Moosazadeh *et al.* [145] designed an UWB monopole antenna, comprising a square patch with square slots and a ground plane truncated with two mirror L-shaped notches. Wu *et al.* [146] presented an UWB band notch antenna having a fork-shaped resonator, for wide bandwidth, and rectangular ground plane. The WLAN band-notch characteristics were achieved by introducing a resonator composed of an open-looped resonator and two tapped lines, at the centre of radiator.

Movahedinia and Azarmanesh [147] enhanced the bandwidth of a printed monopole antenna by using a beveled shape rectangular patch, a trident-shaped feeding structure and a truncated ground plane. The trident shaped feeding structure was realized by loading the patch with two trapezoidal slots. This feeding structure was made up of a splitting network having three ports at the base, which ensure the presence of dominant vertical current modes and prevent the excitation of horizontal currents. They realized band notch characteristic by inserting a semi-octagonal parasitic strip in the antenna.

Deen *et al.* [148] proposed an UWB elliptical monopole antenna with four band-notched characteristics (3.4-3.69 GHz, 5.15-5.825 GHz, 8.5-9.5 GHz and 12-13 GHz). A wider bandwidth was achieved by inserting a semi-elliptical slit into the ground plane. The band notch characteristics for two frequency bands were achieved by embedding two U-shaped slots into the elliptical radiating patch. Band rejection functions for remaining two bands were realized by etching two U-shaped slots into the ground plane. Rouhi *et al.* [149] achieved an ultra-wide bandwidth from a microstrip line fed UWB square monopole antenna by loading the ground plane with T-shaped slots to excite additional resonances. The band notch function was realized by introducing a modified T-shaped conductor-backed plane. Yazdanifard *et al.* [150] enhanced the bandwidth of a printed UWB monopole antenna by using a ground plane with rectangular sleeve and a pair of L-shaped resonator to adjust the electromagnetic coupling effects between the patch and the ground plane. The variable band notch characteristics for two sub bands of WLAN frequency band were achieved by cutting a modified W-shaped slot with variable dimensions on a stepped square radiating patch. Zhang *et al.* [151] introduced band-notch characteristics for WLAN band in a circular UWB monopole antenna by dividing the radiator into three parts.

Mardani *et al.* [152] introduced dual band notch characteristics by using two shorting pins for establishing the connection between the inverted L-shaped stubs on the bottom of the substrate and the patch. Zaker and Abdipour [153] enhanced the bandwidth of a microstrip line fed rectangular monopole antenna by introducing three sequential notches at the two corners of the quasi-square patch to balance the vertical and horizontal surface currents on the patch surface for stable radiation pattern.

Later on, Xiao *et al.* [154] enhanced the bandwidth of a microstrip-fed UWB printed circular-ring monopole antenna by etching multiple steps on the rectangular ground plane. This was followed by Lin *et al.*'s [155] work in which a key-shaped CPW-fed monopole UWB antenna was designed by using two notches at the bottom of the radiating patch and etching a slit on it. Ghobadi *et al.* [156] presented a monopole antenna having UWB characteristics introduced by embedding two shorted rectangular quarter wavelength resonators, which acted as parasitic resonators and excited additional resonances. The WLAN band notch characteristic was achieved by using two other L-shaped quarter-wavelength resonators coupled to the radiating patch.

Ebrahimian and Ojaroudi [157] enhanced the bandwidth of a square monopole antenna by introducing L-shaped sleeves on the ground plane and loading the patch with T-shaped slots. The L-shaped sleeves improved the electromagnetic coupling between the lower edge of the patch and the ground plane. The introduction of T-shaped slots improved the impedance matching at higher frequencies by changing the surface current path. Ojaroudi *et al.* [158] enhanced the bandwidth of a conventional rectangular monopole antenna by using two pairs of slot and sleeve, one on patch and another on ground plane respectively, based on Babinet’s Equivalence Principle and self-complementary structure in feed gap distance.

Eshtiaghi *et al.* [159] enhanced the bandwidth of a microstrip line fed semi-elliptical monopole by carving two sectors on top side of it and by using curved ground plane. The band rejection function for WLAN band was realized by loading the patch with two arc shaped slot. Zhang *et al.*[160] enhanced the bandwidth of an elliptical UWB monopole by loading the radiator with two semi-elliptical slots along its edges and by using asymmetric feeding. The band notch prototype was also designed by incorporating a switch between the two slots on one side.

In 2011, Teirab *et al.* [161] improved the return loss performance of a CPW-fed disc monopole antenna by using a tapered co-planar waveguide transmission line. Lak *et al.* [162] presented an UWB antenna comprising an inverted trapezoidal radiating patch, having length of its smaller parallel side equal to the feedline width for smooth transition resulting into bandwidth enhancement, and a modified rectangular ground plane. Single band notch function was realized by loading the ground plane with two L-shaped quarter waveguide resonators shunt connected to the radiating patch by two shorting tracks.

Sarbazi *et al.* [163] presented a planar rectangular UWB monopole antenna with variable frequency band-notch characteristic. The ultra-wideband characteristic had been achieved by using two L-shaped strips on the top edge of the ground plane whereas band-notch characteristic was achieved by embedding two L-shaped slits on the ground plane. Yazdi and Komjani [164] introduced band-rejection characteristic around 5.5 GHz in an UWB circular monopole antenna by using a mushroom-like electromagnetic band-gap (EBG) structure. Azim *et al.* [165] enhanced the bandwidth of a microstrip line fed square monopole antenna by loading the partial ground plane with multiple slots on its upper edge to make it suitable for UWB applications.

Liu *et al.* [166] derived a CPW-fed UWB monopole antenna from a rectangular patch antenna. Its radiating patch was derived from a rectangular patch antenna by loading it with an open end circular ring slot and an inverted U-shaped slot along with two horizontal slots on the CPW ground plane. Due to the introduction of parasitic patch and the embedded ground slots, dual resonant modes got excited resulting into overall impedance bandwidth enhancement. Elsheakh *et al.* [167] proposed a microstrip line fed UWB monopole antenna composed of V-shaped feed plate, parallel V-shaped patches and newly designed EBG structures for the bandwidth enhancement. Mitra *et al.* [168] designed a planar UWB monopole antenna with dual band notch characteristics. The band notch characteristics had been introduced by inserting a strip and metallic ring above and below the substrate.

Peng and Ruan [169] used conventional mushroom-type EBG and edge-located vias mushroom-type EBG structure to introduce band notch function for wireless local-area network interference bands (5.2-and 5.8-GHz bands) in the passband of an UWB elliptical planar monopole antenna. Lu *et al.* [170] presented an elliptical UWB monopole antenna with minimized ground plane effects. A good impedance matching had been achieved by tapering the microstrip feed line near the elliptical radiator. The ground plane effects had been miniaturized by loading the ground plane with slots on its top edge which had changed the current distribution.

Mishra *et al.* [171] proposed a parallel metal-plated tuning fork shaped omni-directional antenna for UWB application. The omni-directional radiation bandwidth had been increased by using rectangular strips on both sides of a semi annular ring monopole antenna. The cross polarization had been reduced by using metal plated circular and annular ring radiator.

Mishra *et al.* [172] designed a microstrip line fed dual band antenna for Bluetooth and UWB applications by introducing a rectangular monopole in the central portion of U-shaped monopole antenna, designed by placing two rectangular strips at the top of the two arms of a semi annular ring, to resonate over Bluetooth band leading to tuning fork shaped dual band monopole antenna. The band notch characteristics for the WLAN band had been achieved by loading the rectangular ground plane with two L-shaped slots and two symmetrical step slots at both edges and a rectangular slot at the center. Koohestani *et al.* [173] presented a microstrip line fed UWB planar monopole antenna comprising a dome-topped, bowl-shaped patch and a truncated ground plane structure with its upper edge tapered and including a notch below the feed-line in the vicinity of the patch. Azarmanesh *et al.* [174] achieved single and dual band notch characteristics for the WLAN, C and WiMAX bands in a CPW fed rectangular UWB monopole antenna by loading the five stepped staircase radiator with two symmetric and asymmetric quarter wavelength spiral slits.

Ojaroudi *et al.* [175] enhanced the bandwidth of a microstrip line fed square monopole antenna by loading the patch with an inverted T-shaped slot and adding an inverted T-shaped conductor-backed plane in the ground plane to excite additional resonances. Li *et al.* [176] enhanced the bandwidth and reduced the size of a microstrip line fed UWB monopole antenna by loading the special-shaped radiation patch with straight & cross gaps and the ground plane with a combination of rectangular & triangular slots replacing the triangular slots of the initial UWB antenna. Same authors [177] introduced dual band notched characteristics in an UWB monopole antenna comprising a trapezoidal ground plane loaded with a rectangle slot, by loading the Y-shaped monopole radiator with modified complementary co-directional split ring resonator (SRR).

In parallel to this, Thomas *et al.* [178] designed a CPW fed UWB beveled monopole antenna for portable devices. The size of the antenna was reduced by beveling the monopole & ground plane edges and introducing a rectangular notch in the ground plane beneath the feed monopole transition. Zhou *et al.* [179] introduced dual band notch characteristics in an UWB annular ring monopole antenna by adding a pair of Y-shaped strips to the annular ring, and etching an inverted Ω-shaped slot on the patch. Srifi *et al.* [180] investigated two configurations of an UWB circular disc monopole antenna i.e. with single transition and double transitions between the microstrip feed line and the radiator. Ojaroudi *et al.* [181] presented an UWB monopole antenna with single band notch function. It was made up of a square-ring radiating patch with a pair of T-shaped strips protruded inside the square ring, for band notch generation, and a coupled π-shaped strip and a ground plane with a protruded strip, for a wide usable fractional bandwidth. Liu *et al.* [182] studied a wideband antenna composed of a trapezoid ground plane and an elliptical monopole patch which is fed by a modified tapered CPW line for wideband performance.

Nouri and Dadashzadeh [183] presented an UWB printed monopole antenna with filtering characteristics for Dedicated Short-Range Communication (DSRC) systems and WLAN bands. It comprised a radiating patch with arc-shaped step, for stable H-plane radiation patterns at high frequencies and wide impedance bandwidth, notched by removing two squares at the bottom, to compensate the effect of minimizing the size of the antenna on the lowest frequency, and a modified shovel-shaped defected ground structure (DGS). Ghaderi and Mohajeri [184] presented a microstrip-fed wide-slot antenna composed of an elliptical patch connected to a trapezoid one and ground plane with a hexagonal slot etched on it. The wideband matching had been provided by using a smoothly tapered line between the radiating patch and microstrip feed line.

Peng and Ruan [185] introduced band notch characteristics in UWB antenna by using mushroom-type electromagnetic bandgap (EBG) structure. Mishra *et al.* [186] introduced dual band characteristics in an UWB monopole antenna by using a fork-shaped radiating patch and a rectangular ground plane. Yan *et al.* [187] introduced dual band notch characteristics in a microstrip-fed ultra-wideband antenna by etching a pair of L-shaped slots in the ground plane for WiMAX and an eccentric ring & a stub with an arc structure for WLAN. Lotfia *et al.* [188] introduced triple band notch characteristics in a microstrip fed tapered monopole and a CPW fed tapered monopole by loading the patch with three broken ∩-shaped slots. Akbari *et al.* [189] enhanced the bandwidth of a square monopole by using three techniques: (i) steps on the patch and ground plane proportionately; (ii) a partially ground plane; and (iii) a single square-shaped notch on the ground plane.

In 2012, Koohestani and Moghadasi [190] used three techniques for bandwidth enhancement i.e. (i) a slot on the patch, (ii) a trapezium ground plane to the CPW line, and (iii) an inverted triangular transition junction between the CPW feed line and radiation element, to design an UWB antenna comprising a loop shaped radiating element. Rahim *et al.* [191] proposed a microstrip line fed asymmetric shaped UWB monopole antenna with circular polarization (CP).

Lu and Yeh [192] achieved UWB characteristics in a monopole antenna by gap coupling a rectangular parasitic patch to arc-shaped radiating patch. Kerarti and Seriah [193] designed an UWB monopole antenna by using diamond shaped patch along with partial ground and stepped transformation on patch. Lvxia *et al.* [194] presented an UWB planar monopole antenna comprising a trapezoidal patch with semi-circular load and four discontinuities at the feed end, stepped micro-strip feed line and a ground plane on the bottom of the substrate. Lu *et al.* [195] used the concept of strong coupling between the slot modes and ground coupling modes to make the characteristics modes insensitive to the dimensional changes in the ground plane and proposed two UWB monopole antennas with slots on their ground planes. First antenna comprised an elliptical radiator and rectangular-shaped ground plane whereas the second antenna consisted a swan-shape radiator and rectangular-shaped ground plane.

Majidzadeh *et al.* [196] designed a microstrip-fed UWB monopole antenna composed of a quasi-square radiating patch with three notches and a modified ground plane with a rectangular slot to achieve wider impedance bandwidth. Zhang *et al.* [197] achieved WLAN band notch in an UWB CPW coupled fed elliptical monopole antenna by etching an arc slot on the radiating patch. Yang *et al.* [198] designed a ring shaped monopole antenna having a quarter wavelength tuning stub, to avoid the interference with WLAN network, a pair of two steps impedance transformed CPW-feed line and an arc slot in the ground for covering the UWB frequency range. Rostamzadeh [199] designed an UWB monopole antenna composed of a stepped square radiating patch, two rod shaped parasitic structures in the ground plane for band-notch function at 5.1/5.9 GHz and a notched ground plane with two novel V-shaped slots for a wide impedance bandwidth.

Foudazi *et al.* [200] integrated GPS, GSM and WLAN bands in an UWB monopole antenna by removing the central part of the diamond shaped patch and inserting several quarter wavelength narrow strips in the notched region without affecting the UWB behavior and the dimensions of the antenna. Mehranpour *et al.* [201] introduced dual band characteristics in an UWB monopole antenna by loading the square radiating patch with a pair of L-shaped slits, and an E-shaped slot. Its ground plane had a V-shaped protruded strip for a wide usable fractional bandwidth.

Tilanthe *et al.* [202] presented a printed UWB monopole antenna with dual band notch characteristics, introduced by using an inverted ‘L’ shaped slot & ‘J’ shaped slot in the stepped rectangular patch for 3.4 GHz band rejection and ‘U’ shaped slot on radiating patch & a spur line filter in the microstrip feed line for non-radiating characteristics at 5.5 GHz. Koohestani *et al.* [203] achieved band-notch characteristics for 5GHz WLAN and 8GHz ITU bands by loading the patch with a padding patch printed on a small single-layer piece of commercial substrate.

Jiang *et al.* [204] achieved dual band notch characteristics by etching two complementary split ring resonator (CSRR) structures on the inner patch of an UWB monopole antenna. Darvish *et al.* [205] designed a CPW-fed UWB monopole antenna with multiple band notch characteristics, obtained by using multiple modified U-shaped (MU) slots on the beveled rectangular radiating patch. Boudaghi *et al.* [206] achieved frequency reconfigurability in a monopole antenna for five frequency bands by using a switchable slotted structure, composed of four PIN diodes along with DC blocking capacitors, on the ground plane. Deng *et al.* [207] designed a flexible triple band UWB monopole antenna for WBAN by using a miniascape-like strip composed of an S-shaped strip, a U-shaped strip, and an I-shaped strip. The bandwidth had been enhanced by loading the ground plane with quarter-circle notches. Sung [208] designed a circular shaped UWB antenna with two short-circuited folded stepped impedance resonators (SIRs) for dual band rejection function realization.

Mishra *et al.* [209] introduced dual band notches by embedding C-shaped slot on the circular patch and a pair of L-shaped slots on the rectangular ground plane. Mahdavi *et al.* [210] presented a CPW fed UWB circular monopole antenna consisting a rectangular patch and a quarter of disc. By using these circles in shaping the radiating element, a smooth curved structure is formed. Aboufoul *et al.* [211] designed an ultra-wideband (UWB) microstrip monopole antenna with reconfigurable multiband function by using GaAs field effect transistor (FET) switches to connect multiple stubs of different lengths to the main feed line of the monopole.

Fei *et al.* [212] presented a CPW-fed UWB monopole antenna and an asymmetric coplanar strip (ACS) -fed half monopole antenna. The introduction of ACS feeding miniaturized the antenna size by 50%. For the ACS-fed antenna, quasi-omnidirectional patterns were obtained in H-plane and distorted radiation patterns in the E-plane especially at higher frequencies which may be due to its inherent unsymmetrical structure. Sun *et al.* [213] investigated the performance of different UWB monopole antennas for body-centric wireless networks by using liquid-body phantom. They put forward a conclusion that the hexagonal radiator had better performance than elliptical antenna in term of average peak gain and efficiency.

Moghadasi *et al.* [214] proposed another configuration of an UWB slot antenna. Its VSWR performance was improved by using a technique comprising of open-end stubs at the periphery of the ground-plane in the vicinity of the feed-line. The WLAN band notch was generated by using an effective conductor backed plane structure. Reddy *et al.* [215] proposed an edge feed printed elliptical antenna configuration. The partial ground plane was used to improve the gain performance which on another hand led to the generation of surface waves, which caused destructive interference and increased the cross-polar component at higher frequencies. To provide an in-phase excitation the parasitic patches had been introduced on the partial ground plane.

In 2013, Karimabadi and Attari [216] enhanced the bandwidth of a CPW-fed circular disc monopole antenna by etching a semi-elliptical notch at the ground plane.

They introduced the band rejection characteristics for WLAN band by loading the modified ground plane with two U-shaped slots. Mandal and Das [217] introduced band notch for WLAN band in a microstrip-line fed UWB plaque monopole antenna by loading the radiating patch with inverted U-shape slot or Π-shape slot or Λ-shape slot. Two other band notch functions for WiMAX (3.25–3.75 GHz) and down link of X-band satellite communication system (7.25–7.75 GHz) were realized by introducing two half wavelength U-shaped slots in the radiating patch.

Sung [218] embedded a modified H-shaped resonator with an additional outer line beside the microstrip feedline to generate band reject function for WiMAX, WLAN and the X-band satellite communication bands in a printed microstrip-fed monopole ultra-wideband (UWB) antenna. Kim *et al.* [219] proposed a triple band-notched UWB elliptical monopole antenna. Band rejection for WiMAX and ITU bands were realized by using a spiral resonator whereas for WLAN band a complementary split ring resonator (CSRR) structure had been utilized. Yazdi and Komjani [220] obtained dual band-notch characteristics for WiMAX and WLAN bands by inserting a pair of two slots in the ground plane as well as adding a pair of arc-shaped parasitic strips around the radiating element.

In parallel to this, Gautam *et al.* [221] designed a CPW fed hexagonal shape UWB monopole antenna by using a hexagonal radiating patch obtained by modifying the shape of a rectangular patch antenna and extending the CPW ground plane on both sides of the radiator. As the radiator is surrounded by a metal ground plane for reducing the antenna area, the small gap between the radiator and the ground plane is a major factor to cause over-strong capacitive coupling. Sefidi *et al.* [222] designed an UWB monopole antenna comprising a trapezoid shaped radiating patch with two modified

L-shaped notches and a partial rectangular ground plane. The modified L-shaped notches affected the electromagnetic coupling between the lower edge of the modified trapezoid-shaped patch and ground plane to broaden the impedance bandwidth by improving the impedance matching performance at middle frequencies within the operating frequency range.

On the other side, Xu *et al.* [223] presented a CPW fed UWB monopole antenna comprising a rectangular radiator loaded with semi-elliptical slot and ground plane connected to two extended open-circuited stubs. Moghadasi *et al.* [224] presented a CPW-fed UWB monopole by using a V-shaped radiator, defected feedline and defected ground plane. The impedance bandwidth was enhanced by loading the feedline with a slot along with an open stub and DGS. The radiating patch was loaded with rectangular slot and a slot loaded rectangular backed plane was introduced to realize the dual band notch characteristics.

Later, Krishna and Kumar [225] presented a dual polarized UWB monopole antenna by using an asymmetrically fed rectangular patch chamfered at its one corner and loaded with an hour-glass shaped slot. The geometry perturbation, asymmetrically feeding and slot loading resulted into dual polarization of the antenna structure by enhancing the cross polarization in the frequency band of 4.4-6.6 GHz. Guo *et al.* [226] enhanced the bandwidth of a microstrip fed UWB monopole antenna by loading the ground plane with two additional slots, resulting into the lowering of the lower cutoff frequency, and introducing mushroom shaped EBG structure.

Sarkar *et al.* [227] presented an UWB monopole antenna comprising a radiator having half ellipse at its lower section with rectangular section in the upper section and a rectangular ground plane having two beveled edges loaded with two semi-circular slots at its bottom edge. The beveling of the ground edges and loading it with semi-circular slots resulted into the bandwidth enhancement. Dual band notch characteristics were introduced by loading the radiating patch with two concentric annular slots with splits in them in opposite side. Kim and Yun [228] designed an UWB monopole antenna consisting a C-shaped radiator along with an inverted L-shaped coupled strip extended from the ground plane. The impedance bandwidth had been enhanced by utilizing a loop-type resonant mode and an electromagnetic coupling effect that were based on a combination of both elements.

Sun *et al.* [229] presented an UWB antenna consisting an elliptical radiator fed by a microstrip line having three-step staircases on both sides and a slot loaded rectangular ground plane. Jeng and Luo [230] designed an UWB annular ring monopole antenna. They introduced dual band notched characteristics by embedding a rectangular stub in the annular ring radiator and connecting the radiator with an elliptical backed plane radiator by means of a shorting pin. Gautam and Kanaujia [231] proposed an UWB monopole antenna with a modified rectangular radiator and conventional rectangular ground plane. Dual band notch characteristics were achieved by loading the radiator with two C-shaped slits symmetrical to the radiator centre.

Ojaroudi *et al.* [232] presented an UWB monopole antenna derived from a conventional rectangular patch and having an inverted fork shaped slit in the partial rectangular ground plane for the bandwidth enhancement. Dual band notched functions were included by using coupled inverted U-ring strip on the radiating patch. It perturbed the resonant response and also acted as a parasitic half-wavelength resonant structure electrically coupled to the cross-shaped monopole. Same authors [233] came forward with an UWB rectangular monopole antenna whose bandwidth was enhanced by loading the partial rectangular ground plane with E-shaped slots to excite additional resonances. They achieved dual band notched characteristics by introducing a W-shaped conductor back plane and loading the radiating patch with modified T-shaped slot. Again the same authors [234] introduced band notch characteristics in an UWB rectangular monopole antenna by loading the ground plane with rectangular slots and adding protruded Γ-shaped strips to the radiating patch.

Ojaroudi and Ojaroudi [235] designed an UWB monopole antenna with dual band notch function by loading the ground plane with an inverted fork shaped slot for larger bandwidth and by converting a conventional rectangular monopole radiator to a G-shaped radiator loaded with a rotated Γ-shaped slot for band notch functions. Same authors [236] enhanced the bandwidth of a rectangular UWB monopole antenna by loading it with inverted T-shaped slot with an inverted T-shaped parasitic element, which excited additional resonances. They introduced dual band notch characteristics by loading the rectangular radiating patch with inverted T-shaped slot surrounded by C-shaped slot and by the addition of an inverted T-shaped parasitic element into the inverted T-shaped slot on the radiating patch.

Lages *et al.* [237] presented two elliptical UWB monopole antenna structures fed by trapezoidal microstrip feed line. Moghadasi *et al.* [238] presented an UWB monopole antenna whose radiating patch comprises a trapezoid on top of a rectangle with a protrusion at its base which inserts neatly into a U-shaped structure that is connected to a feed-line. The dual band notch functions for WLAN & ITU-R bands were realized by nesting symmetrical meander slots in the shape of Γ and U. Aghdam and Varkiani [239] designed an UWB monopole antenna with dual band notch characteristics by using a balloon shaped radiating patch loaded with an inverted U-shaped slot and two circular ground plane structures in the back plane.

Zhang *et al.* [240] designed a CPW fed elliptical monopole antenna consisting a trapezoidal patch on other side of substrate to couple the energy from the feedline to the elliptical radiator. The elliptical radiator was loaded with one, two, three arc slots to achieved single, double and triple band notch characteristics respectively. Ellis *et al.* [241] presented a wing-shaped monopole antenna. The wing shaped radiator had been derived by adding two rectangular strips at the top edge of the rectangular patch to form a stepped structure and then etching a rectangular notch from the stepped structure. The band-rejection function for the frequency range of IEEE INSAT/super-extended C-band is achieved by adding a rectangular strip at the hollow portion of the wing monopole. Sun *et al.* [242] introduced reconfigurable band-notch characteristics in an elliptical UWB monopole antenna by etching a meander-defected-ground-structure (meander-DGS) on the ground plane underneath the feedline and loading the DGS with a varactor diode.

Aboufoul *et al.* [243] presented a circular monopole UWB antenna having a circular radiator and a partial rectangular ground plane with notches at its upper corners. The pattern reconfigurable property was achieved by incorporating four P-I-N diode switches and two arc shaped parasitic elements along the partial rectangular ground plane. Kang *et al.* [244] introduced WLAN band notch characteristic by loading the half elliptical ring monopole antenna with a U-shaped slot. Wu *et al.* [245] enhanced the bandwidth of a conventional rectangular monopole by loading the ground plane with a lateral L-shaped slot. Reconfigurable quad band notch characteristics for the frequency bands of WiMAX, INSAT, lower WLAN and higher WLAN were achieved by loading the radiating patch with four U-shaped slots. A band notch function could be removed by shorting the corners of corresponding U-slot.

Ojaroudi and Ojaroudi [246] enhanced the bandwidth of a microstrip line fed square monopole by loading the ground plane with inverted Γ-shaped slit and an inverted U-ring shaped slot for excitation of additional resonances. The reconfigurable band notch function was realized by using a PIN diode in U shaped slot of ground plane. Karimabadi and Attari [247] enhanced the bandwidth of a CPW-fed disc monopole antenna by removing semi-elliptical portion from the top edge of the ground plane. Band notch characteristic for WLAN band were achieved by loading the ground plane with two U-shaped slots.

Thwin [248] designed two UWB monopole antenna structures. One structure comprised a microstrip line fed circular patch with a pair of three-step staircase notch and a truncated ground plane with two-step staircase notches. In the second structure, the microstrip feed of previous structure was replaced by CPW fed with a staircase notch. Yazdi and Komjani [249] introduced dual band rejection function in a circular UWB monopole by loading the ground plane with a pair of quarter wavelength slots and adding a pair of half wavelength arc shaped strips to the radiator. Liu *et al.* [250] introduced deep band notch characteristic in a microstrip fed elliptical monopole by etching a pair of meander lines adjacent to tapered feedline and another pair of meander lines on the top edge of the ground plane. Sreenath *et al.* [251] miniaturized and modified a monopole by folding the radiator.

In 2014, Shrivastava *et al.* [252] presented M-shaped monopole-like UWB slot antenna with a tilted rectangular slot at the lower right hand corner of radiating patch and rectangular slot loaded ground plane. Ojaroudi [253] enhanced the bandwidth of a conventional rectangular UWB monopole with a conventional rectangular ground plane by loading the ground plane with rotated L-shaped slots to provide additional current paths along with changes in the inductance and capacitance of the input impedance. The bandwidth is further enhanced by introducing rotated L-shaped conductor backed plane structures, which introduced additional electromagnetic coupling between the bottom edge of the patch and the ground plane. Ray *et al.* [254] enhanced the bandwidth of an elliptical monopole antenna [72] by loading the elliptical patch with two pairs of elliptical slots. The introduction of slots affected the higher modes of the elliptical monopole and increased the higher band-edge.

Manohar *et al.* [255] enhanced the bandwidth of printed triangular monopole UWB antenna by replacing the partial rectangular plane with round corner ground plane and introducing a transition between the microstrip feedline and the radiating patch. The transition involved stepped changes in impedance function (i.e., a single-section transformer) resulting into transformer bandwidth enhancement as antenna impedance becomes closer to the characteristic impedance of the microstrip feed line. Afterwards, Neto *et al.* [256] presented a circular monopole antenna with enhanced bandwidth, achieved by loading the partial rectangular ground plane with a rectangular edge notch. The introduction of notch reduced the capacitance in the connection region between the microstrip line and the circular conductor patch, leading to improved impedance matching. The band notch characteristic was introduced by etching a circular split ring resonator on the back side of substrate besides the circular radiating patch.

Rahimi *et al.* [257] designed a tapered UWB monopole antenna having the radiator and ground plane on the one side of the substrate. The microstrip feed line was on another side of the substrate. The radiator is fed by using via between the feed line and the radiator. Single band notch characteristics for the WLAN bands had been achieved by loading the patch with L-shaped and C-shaped slots. Dual band notch characteristics for the two bands had been achieved simultaneously by placing an F-shaped stub along the feed line.

Sarkar *et al.* [258] presented a semielliptical microstrip fed UWB monopole antenna with semi-elliptical ground plane. The radiator was loaded with a pair of elliptical CSRR slots to achieve the dual band notch characteristics for the frequency range of WiMAX and upper WLAN frequencies. The third band notch for the frequency range of X-band was achieved by placing two rectangular SRR elements of dimensions, calculated using standard equations, near the junction of the feedline and the radiating patch. Venkata *et al.* [259] proposed an UWB monopole antenna comprising a semicircular radiating patch and a modified ground plane with two bevels at upper edge. The triple band notch characteristics for the frequency range of WiMAX band, WLAN band and X-band downlink satellite communication band had been achieved by introducing two round shape slots on the radiating patch (for WiMAX and WLAN) and a pair of rotated V-shape slot on the ground plane.

Luo *et al.* [260] designed a modified UWB monopole antenna consisting an U-shaped radiating patch and partial rectangular ground plane with square slots. Triple band-rejection functions were realized by adding I-shaped & L-shaped stubs in the square slots of ground plane and placing resonant open-circuited stubs adjacent to the antenna edges. Kazim *et al.* [261] presented a rectangular UWB monopole antenna. The upper two corners of the radiating patch were truncated. The radiating patch was loaded with an inverted U-shaped slot and the partial rectangular ground plane was loaded with a rectangular notch to achieve dual band-notch characteristics. Shrivastava *et al.* [262] presented a microstrip line fed A-shaped monopole like slot antenna for UWB applications. The bandwidth performance was improved by using a rectangular ground plane loaded with two rectangular slots and four extended stubs.

Aghdam [263] designed a CPW-fed UWB monopole antenna composed of a radiator combining a semi-circular and a rectangular patch and an edge-curved ground plane. He introduced tunable band notch characteristics by loading the radiator with a π-shaped slot and then adding a varactor diode in the middle of slot. Singh *et al.* [264] designed a monopole antenna for UWB and Bluetooth applications. It comprised a truncated U-shaped radiator, microstrip feedline and partial ground plane. They introduced dual band notch characteristics for WiMAX and WLAN frequency bands by introducing a T-shaped stub on the radiator and mushroom shaped EBG structures along the feedline respectively. Cai *et al.* [265] introduced triple band notched characteristics for the frequency bands of WiMAX, WLAN, and ITU by loading the feeding line of a double fed UWB rectangular monopole antenna with two circular slots.

Fakharian and Rezaei [266] achieved an ultra-wideband performance by using palmate leaf shaped radiator and truncation of the CPW ground plane. Ellis *et al.* [267] designed a unidirectional UWB circular monopole antenna by replacing the conventional microstrip line feed with a wrench shaped feed line, which introduced vertical currents in the structure and reduced horizontal currents at high frequencies. Parkash and Khanna [268] derived a triple band rectangular monopole antenna from a T-shaped monopole by the addition of multiple rectangular strips. Hanapi *et al.* [269] enhanced the bandwidth of an elliptical monopole antenna by replacing its rectangular ground plane with eleven step slot loaded rectangular ground plane.Deng *et al.* [270] added an additional resonance at 2.44 GHz to achieve WLAN band by introducing a pair of mushroom shaped self-complementary resonators on to the ground plane. They achieved band notched characteristics for WiMAX and C bands by introducing a pair of mushroom shaped self-complementary resonators into the radiator.

Wang *et al.* [271] introduced dual rejection functions in a cup shaped UWB monopole antenna by loading the CPW ground plane edges with a pair of L-shaped slots and by loading the radiator with two symmetrical L-shaped stubs. Malik and Kartikeyan [272] designed a circular monopole UWB antenna fed by a stepped feedline. It comprised a raised cosine shape profile ground plane having a nonlinear taper with given end diameters and length for ensuring good impedance match over a broad frequency range. They loaded the circular monopole with a slot to achieve the WLAN band-rejection function. Khandelwal *et al.* [273] enhanced the bandwidth and suppressed the cross polarization levels by using defected ground plane. Thajudeen *et al.* [274] enhanced the bore sight gain of a planar stair-like monopole antenna by incorporating gate like ground plane, which alleviated the squinting effects in the gain patterns at higher frequencies, and by stacking parasitic patch.

Siddiqui *et al.* [275] introduced band notch characteristics for the frequency around 6.38 GHz in a CPW fed circular monopole antenna by printing two square SRR on the back side of radiator. Zhang *et al.* [276] achieved triple band-notched characteristics in a CPW fed UWB antenna by introducing a stepped impedance resonator-defected ground structure (SIR-DGS) and fork-shaped stubs. Ershadh *et al.* [277] designed an UWB monopole antenna by adding beveled stubs along the circular disc monopole circumference and by using tapered feedline for wide impedance matching.

Koohestani *et al.* [278] designed a polarization diversity UWB antenna by arranging two CPW-fed monopole antenna structures perpendicular to each other. Ojaroudi *et al.* [279] enhanced the bandwidth of a square monopole by introducing C and L-shaped conductor backed plane structures to excite additional resonances. The embedded structures were connected by PIN diodes whose ON/OFF situation reconfigures the band to be notched among WLAN/ITS/ITS bands. Ojaroudi *et al.* [280] enhanced the bandwidth of a square monopole by introducing an inverted T-shaped strip and a pair of T-shaped conductor backed plane strips to the ground plane. The dual band rejection functions covering WiMAX, WLAN and C bands were realized by replacing the square monopole with coupled U-shaped ring radiator. Wu *et al.* [281] introduced reconfigurable dual band notch characteristics for WiMAX & WLAN bands in a circular monopole by loading the radiator with an arc shaped slot and by loading the feedline with a C-shaped slot.

Ojaroudi [282] proposed a circular UWB monopole antenna with dual band notch characteristics. The radiator was loaded with a rotated T-shaped slit to achieve WiMAX band rejection and the feedline was embedded with a rotated **Ω**-shaped slit for WLAN band rejection. Ojaroudi *et al.* [283] presented a fan shaped UWB monopole with triple band notch characteristics. The partial rectangular ground plane was loaded with square slots and then a pair of protruded T-shaped strips was embedded into those square slots to achieve wideband performance. A pair of L-shaped parasitic strips was added to the radiator for first band notch function. Second and third band rejection characteristics were achieved by loading the feedline with a rotated S-shaped slot.

Ojaroudi and Ghadimi [284] introduced band notched characteristics for intelligent transport system (ITS) band in a square monopole antenna by using a cross shaped conductor backed plane. The wideband performance was achieved by loading the ground plane with a pair of rotated H-shaped slots. Ojaroudi [285] proposed a square ring UWB monopole antenna with dual band notch characteristics. The wideband performance was achieved by loading the ground plane with rotated E-shaped slots. The square ring radiator was protruded with a pair of rotated T-ring strips to generate dual band notch functions for WLAN, WiMAX, and C bands.

Varkiani *et al.* [286] presented an UWB monopole antenna fed by an H-shape slot loaded staircase CPW feedline. The modified ground plane comprised four grounded semicircular metallic strips placed at the corners of the central circular slot for wideband performance. Mandal and Das [287] achieved dual band notch characteristics for WiMAX and WLAN bands in a hexagonal monopole antenna by introducing two electromagnetic band gap structures, one for each rejected band. Verma and Kumar [288] designed an egg shaped UWB monopole antenna by using the equations of Newton's diverging parabolas curve. The design equations were also developed.

Xiao *et al.* [289] designed a two-step beveled UWB monopole antenna consisting two differently sized rectangular patches connected with the chamfered corner of 45^o and partial ground plane loaded with L shaped notches. The band notch function for WLAN was realized by loading the feedline with a pair of flag shaped slots, acting as the stepped impedance resonator (SIR). Ray and Thakur [290] achieved a wideband performance from a pentagonal UWB monopole antenna by truncating the feeding vertex in order to reduce the impedance at feeding point. An equation for calculating the side length of the pentagon to achieve desired lower frequency was also presented by equating the surface area of pentagon equal to that of a cylindrical wire monopole.

In 2015, Ershadh [291] presented the detailed methodology of designing the antenna structure presented by his group [277]. Silveira *et al.* [292] presented a microstrip line fed UWB monopole antenna. The radiator was derived by attaching two distinct elliptical monopoles along their major axes. The ground plane was comprising a triangular groove, whose centre was aligned with the feedline.

Kahar *et al.* [293] designed and investigated a dodecagon UWB monopole antenna for breast tumor detection applications. Srivastava and Mohan [294] proposed a dual band notched UWB monopole antenna. Its radiator was derived from a circular patch by subtracting three similar circular arcs from the reference patch. The bandwidth was enhanced by introducing three notches in the partial rectangular ground plane. Dual band notch characteristics were achieved by loading the radiator with an elliptical slot to reject WiMAX band and by loading the ground plane with G shaped slot to reject WLAN band.

Tang *et al. [*295] designed a convex shaped UWB slot antenna with band notch characteristics for WLAN band. The radiator was a convex shaped patch loaded with elliptical and rectangular slots. The partial rectangular ground plane was loaded with a rectangular slit and a rectangular backed plane or slave radiator was also loaded with rectangular slot. Mandal *et al.* [296] presented a microstrip line fed square monopole loaded with star shaped slot at its centre and four arc shaped notches at its four corners for wideband performance. The band notch characteristics were achieved by using a plus shaped conductor backed plane. Ojaroudi and Ghadimi [297] designed a microstrip line fed rectangular monopole antenna for UWB microwave imaging applications by loading the rectangular ground plane with rotated E-shaped slot and an E-shaped conductor backed plane.

Srivastava *et al.* [298] loaded the partial rectangular plane of a ring shaped monopole with rectangular slots to achieve wideband performance. Three band notch functions for WiMAX, WLAN and X band were realized by loading the radiator with an elliptical spilt ring slot (ESRS) and two quarter wavelength arc-shaped slots along with a pair of single rectangular split ring resonator near the feed line.

Mandal and Das [299] enhanced the bandwidth of a spanner monopole by loading the radiator with 2-step notches and the ground plane with a rectangular notch. The Bluetooth band was integrated by loading the patch with a rectangular notch and embedding a rectangular strip in that notch. The band rejection function for WLAN band was realized by using a mushroom type EBG structure. After this, Wu and Liu [300] came forward with a symmetrically fed twin shaped UWB monopole antenna. The WLAN band notch characteristics were achieved by loading the antenna with a pair of L-shaped slots.

Further, Siddiqui *et al.* [301] introduced dual band frequency notch centered at 5.34 & 7.95 GHz and wideband frequency notch for the frequency band of 6.2-6.9 GHz in a CPW fed circular monopole antenna by loading two pairs of split ring resonators on the back side of CPW feedline. Thereafter, Bekasiewicz and Koziel [302] designed an elliptical UWB monopole antenna with meander line and a pair of slits by using Surrogate based optimization method involving an auxiliary coarse-discretization EM model for reducing the optimization time and by using Penalty function approach to reduce the antenna footprint.

1.2.2 Fractal Antenna

The term “Fractal” means linguistically “broken” or “fractured” from the Latin “fractus”. Fractals are geometrical shapes, which are self-similar, repeating themselves at different scales. The original inspiration for the development of fractal geometry came largely from an in-depth study of the patterns of nature.

Several fractal functions were developed by classic mathematicians like G. Cantor (1872), G. Peano (1890), D. Hilbert (1891), H.V. Koch (1904), W. Sierpinski (1916), G. Julia (1918) and other personalities. These functions played an important role in Mandelbrot's work (1970s) [303-304] of coining the term “fractal” for the first time to describe a family of complex shapes that possess an inherent self-similarity in their geometrical structure. Then the practical applicability of fractals is explored in different branches of science and technology.

Fractal electrodynamics is one of those explored branches of technology. In this research area, the fractal geometry is combined with electromagnetic theory for the analysis and design of antenna systems apart from the traditional Euclidean geometry. This new and rapidly growing field of research is referred to as fractal antenna engineering. Since fractal geometry is an extension of classical geometry, its recent introduction availed the engineers with the unprecedented opportunity to explore a virtually limitless number of previously unavailable configurations of new and innovative antenna structures. There are a number of geometric properties used to characterize or describe fractals [305]. One is the characteristic of self-similarity, in which small regions of the geometry duplicate the whole geometry, only on a reduced scale. Second is the characteristic of self-affinity, in which small regions of the geometry are not identical to the whole geometry, but are skewed or distorted and on differing scales. Third is the space filling property, due to which electrically very long curves can be fitted into a compact size leading to antenna miniaturization and bandwidth enhancement. Due to the complex, uneven, highly convoluted and rough geometry, fractal antennas have enhanced radiation properties. [305-306]

In 2004, Elkamchouchi and Abouelseoud [307] designed UWB fractal antenna operating in the K, Ka and millimeter sub wave range by using Sierpinski Gasket Triangular patch. In parallel to this, Ghali [308] designed an UWB Hilbert curve wire monopole antenna by using resistive loading in the wire monopole for bandwidth enhancement.

It was followed by Lule *et al.*'s [309] work in which they designed a Koch island fractal boundary UWB dipole antenna by using 1/3 rule on a triangular patch antenna and used the FDTD method for the numerical analysis of its behaviour. It was observed that, with the increase in number of iterations the resonance frequency shifts towards lower frequency but the impedance bandwidth decreases along with increase in the Q factor.

One year later in 2005, Lui *et al.* [310] introduced band notch characteristics in an UWB antenna by using fractal structure tuning stub. On the other hand, Kamchouchi and Abonelseoud [311] utilized the concept of Repeated Kernel Array of Microstrip Patches (ReKAMP) to achieve ultra-wide bandwidth by using triangular, circular and square patches.

In the same year, Jamshidifar *et. al.* [312] miniaturized the size of a conventional square patch antenna by introducing fractal concept to it. On the other hand, Madany and Elkamchouchi [313] analyzed an ultra-wideband like fractal microstrip patch antenna by using non-uniform photonic bandgap (PBG) substrate structure. It was observed that PBGs enhanced some modes and weakened others. This concept was used to control the antenna bandwidth.

In 2006, Lui *et al.* [314] designed a fractal slot UWB antenna comprising a microstrip line fed tuning fork shaped radiator and Koch fractal loaded wide slot in the ground plane for band rejection function. In parallel to this, Ding *et al*. [315] presented a CPW-fed ultra-wideband crown circular fractal antenna, designed by using circular patch antenna as a basic structure. On the other hand, Krupenin *et. al.* [316] studied the multiband behaviour of the fractal cluster by means of numerical analysis. They used two dimensional fractal clusters to design an irregular-shaped fractal for ultra-wideband radio systems.

Thereafter in 2007, Ding *et al.* [317] designed an UWB fractal antenna by inscribing triangular fractal structure inside a circular patch antenna.

In 2008, Jahromi and Falahati [318] designed two configurations of UWB fractal antenna by using standing Penta-Gasket-Koch (PGK) fractal radiating patch fed by conventional method in one configuration and by combination of CPW and conventional feeding in another configuration. Jahromi [319] presented a Sierpinski-Carpet-Circular dual band monopole antenna. The radiator structure was achieved by integrating the Sierpinski carpet and the semicircular antenna geometry. It had a conical beam and radiation pattern having no notch on top of antenna such as conventional monopole antenna.

In the same year, Khan *et al.* [320] designed an UWB apollonian shaped circular monopole antenna by using the Descartes circle theorem. The results were compared with that of a circular disc monopole antenna and annular monopole. It was followed by Jahromi and Komjani's [321] work in which they designed two UWB fractal antenna geometries i.e. Penta-Gasket-Koch (PGK) and Complementary-Penta-Gasket-Koch (CPGK) by loading the pentagonal radiating patch with small pentagonal slots to form the Koch curves. On the other side, Park *et al.* [322] designed two configurations of microstrip line fed Tree-shaped UWB fractal antenna by using three rectangular patches in one configuration and three trapezoidal patches in another configuration placing them one over another and partial ground plane. It was demonstrated that the lower band edge frequency is decreasing with increase in number of iterations.

Similarly, Khan *et al.* [323] designed a circular UWB fractal monopole antenna by utilizing the concept of Descartes circle theorem (DCT) with elliptical iterations i.e. by using apollonian geometry. Azari and Rowhani [324] put forward a hexagonal UWB fractal antenna fed by a coaxial probe at its vertices. Peng *et al.* [325] presented a barbell-shaped UWB fractal antenna comprising of two tree-shaped radiating patches along with partial ground plane.

In the same year, Sharma and Shrivastava [326] designed an elliptical UWB fractal antenna by loading the elliptical radiating patch with elliptical slots based on Descartes theorem. Both Yeo *et al.* [327] and Lee *et al.* [328] enhanced the bandwidth of a microstrip line fed trapezoidal UWB fractal antenna by introducing triangular fractal shapes on the patch and by using partial ground plane.

Later in 2009, Kumar *et al.* [329] designed a CPW-fed UWB fractal antenna by inscribing an octagon inside a rotated square patch. Matveev and Potapov [330] designed two UWB fractal antenna configurations based on circular fractal antenna. Krishna *et al.* [331] improved the bandwidth performance of a microstrip fed antenna by introducing 2nd iteration of Koch fractal slot on the rectangular ground plane. Husseini *et al.* [332] designed two microstrip line fed UWB fractal antennae comprising of rectangular patch and partial ground plane. One design comprised a simple rectangular patch and a semicircular ground plane. In another configuration, first design was modified by rounding the corners of the patch and introducing second order Sierpinski carpet. Falahati *et al.* [333] introduced band-notch characteristics in an UWB antenna by loading the radiating patch with binary-tree slots.

Ramadan *et al.* [334] designed an UWB antenna by using trapezoidal connection between the I-shaped feed line and modified 2nd iteration Sierpinski carpet radiating patch with a partial ground plane. The width of the antenna was less than the length due to the fact that on reducing the width, the planar monopole operates similar to printed thin monopole and its ability to retain omnidirectional horizontal patterns over its operating band improves significantly. Kumar and Malathi [335] designed a CPW-fed square shaped fractal dual band antenna.

In 2010, Kumar and Malathi [336] designed a CPW-fed UWB fractal antenna by loading the circular radiating patch with an equilateral triangular slot to create the generator to be used for the 4th order iterative fractal antenna. This antenna structure had very low backscattering losses as compared to a circular radiating patch. On the other hand, Neyestanak *et al.* [337] presented a CPW-fed fractal UWB antenna by using fractal radiating patch and loading the rectangular ground plane with rectangular slot. In parallel to this,

Xu *et al.* [338] modified a square slot UWB antenna to reduce its RCS by introducing Koch fractal curves at the edges of the square slot and by using rectangular loop patch instead of rectangular patch. The antenna bandwidth improved due to the self-loaded characteristics of the fractal antenna after three iterations, which increased the slot perimeter and reduced the metal area of the slot. Kumar and Sawant [339] designed a CPW-fed fourth iterative UWB fractal antenna by inscribing a square patch inside a circular monopole. They [340-341] miniaturized the antenna size and introduced band notch characteristics in the above mentioned structure [339] by loading the feedline with an U-shaped slot. The bandwidth was also reduced. Same authors [342] inscribed inequilateral triangle into the circular patch antenna and then repeated this resulting structure for iterations non-concentrically to achieve ultra-wideband performance.

Thereafter, Wei *et al.* [343] designed a dual band fractal antenna by integrating Koch curves at the edges of a square patch which is loaded with triangular slots. Azari [344] applied a generator on the edges of a wire square loop antenna to design a dual band UWB fractal wire loop antenna. Similarly, Rohani and Azari [345] applied Koch curves at the edges of a wire square loop antenna to achieve the final structure of an UWB Koch fractal antenna. It is followed by Kumar and Bansode's [346] work in which they designed a CPW fed UWB circular fractal antenna based on Descartes Circle Theorem.

In the same year, Kumar and Malathi [347] achieved an ultra-wide bandwidth from a CPW-fed wheel shaped UWB fractal antenna by inscribing triangles in circular patch up to four iterations. Zadeh *et al.* [348] designed a microstrip line fed circular multifractal UWB monopole antenna by combining three segments of equal $\theta(= 2\pi/3)$ but different radius. With the increase of the radius the impedance bandwidth performance was getting improved but the lower band frequency was decreasing and due to the asymmetric antenna structure the feed line position was also affecting the antenna performance.

In 2011, Jahromi *et al.* [349] designed two configurations of the fractal UWB antenna by using conventional feeding for standing fractal antenna in one configuration and a combination of CPW ground plane & conventional feeding in another configuration along with square Sierpinski Carpet fractal patch. Kumar *et al.* [350] derived a wheel shaped UWB fractal antenna by loading a star shaped patch with circular slots and then repeating this structure in further iterations.

Karmakar *et al.* [351] designed an UWB fractal antenna comprising a square patch with rectangular slots acting as fractal structures and a rectangular ground plane having modified von Koch curve shape on its top edge for bandwidth enhancement. The WLAN band-rejection characteristics were achieved by loading the radiating patch with open-ended quarter wavelength slots.

In parallel to these works, Kumar and Malathi [352] designed a diamond shaped UWB fractal antenna. Its generator was creator by dividing a circular monopole into nine equal arcs, scrapping isosceles triangles drawn on the inner side of each arc at an angle of 40^o from the perpendicular bisector of each node (edge of each arc) and etching circular slots on the inner side of each node except the node connected by the feed line to the centre.

Later, Ghanbari *et al.* [353] enhanced the bandwidth of a microstrip line fed circular disc monopole antenna by loading the radiator circumference with circular fractal structures, for miniaturization and reduction of first resonance frequency, and by introducing three slits on the upper edge of the ground plane. Sayidmarie and Fadhel [354] designed two UWB fractal antennae by the superposition of two rectangular and triangular patches. Due to the superposition of small and large rectangular patches along the longer edges, their individual performances got super positioned resulting into overall UWB performance of the composite fractal antenna. Applying the above mentioned idea on triangular patches, two configurations i.e. one with the two triangles sharing the same vertex and one with two triangles having the same slope were designed. The configuration of same vertex offered two slopes, and hence was anticipated to give better performance.

In the same year, Oraizi and Hedayati [355] designed a microstrip line fed monopole UWB fractal antenna composed of a circular metallic patch with a square slot having radial arrow fractal slot patterns on each of its vertices and broken partial ground plane (PGP) with Hilbert fractal slots on it. Kumar and Chaubey [356] designed a CPW-fed UWB fractal antenna by inscribing pentagonal-cut fractals on the circular patch with a modified ground plane and modified feed line.

Jahromi *et al.* [357] introduced dual band-notch characteristics by introducing a binary tree of third iterative order having stem to branch ratio of 1.0 and the branch splitting angle of 120^o to the radiating patch of a CPW-fed UWB fractal antenna. It was concluded that the addition of the band-notch structure to the non-radiating part of the antenna eliminates the undesired spatial-dependent dual band properties. Natarajamani *et al.* [358] designed a CPW-fed UWB fractal antenna having an impedance bandwidth of 3-11 GHz with dual band-notch functions. The band-rejection function was realized by inserting the hook-shaped slits design on the patch whereas for the second band rejection function, two L-shaped slots were etched on to the rectangular ground plane. Ghatak *et al.* [359] designed a CPW-fed circular shaped Sierpinski carpet fractal UWB monopole antenna composed of a circular patch antenna with circular slots of radius calculated by using the one-third rule and introduced band-rejection characteristics by introducing half-wavelength meander line slot.

Li *et al.* [360] enhanced the bandwidth of a CPW-fed Cantor Set Fractal antenna by introducing two symmetrical triangular tapered corners at the bottom of the wide slot. The band notch characteristic was achieved by using T-shaped tuning stub at the top of the wide slot. It was observed that the bandwidth increases further on increasing the cantor order. Kumar and Sawant [361] designed a CPW-fed UWB fractal antenna by inscribing a square in a circle. Kumar and Hake [362] designed an UWB fractal monopole antenna composed of a square patch with fractal structures for additional resonances resulting into wider bandwidth and CPW feeding with a modified ground plane, composed of a rectangular ground plane with three circular sections. Oraizi and Hedayati [363] designed an UWB fractal antenna by introducing Giusepe Peano fractal on the edges of a square patch, and a Sierpinski Carpet fractal on its surface fed by a microstrip line with a matching section and semi-elliptical ground plane. The performance of Giusepe Peano was found to be better than Koch, T-Type, Minkowski fractals. Kumar [364] enhanced the gain of a UWB fractal circular disc antenna by introducing the CPW feeding technique with L-shaped ground. Its cross polarization level was decreasing with increase in frequency.

Pourahmadazar *et al.* [365] achieved an ultra-wideband performance in a microstrip-fed T-shaped patch with semicircular ground plane by introducing modified Pythagorean tree fractal to create additional resonances leading to bandwidth enhancement. Due to the utilization of modified tree fractal, the antenna size also got miniaturized. Xu *et al.* [366] designed an UWB fractal slot antenna by loading a rectangular patch with modified Koch fractal slots having extrusive angles of 90^o instead of conventional 60^o, fed by an offset rectangular microstrip loop instead of an offset rectangular microstrip patch for bandwidth enhancement and reduction of RCS.

Falahati *et al.* [367] enhanced the bandwidth of a Penta gasket Koch fractal antenna by combining it with a planar monopole structure feed to design a hybrid radiating structure. Due to this hybrid structure, the conventional probe feeding is changed to grounded coplanar waveguide feed. Kim *et al.* [368] introduced band reject characteristics in a CPW fed rectangular UWB antenna by etching equation based Hilbert curve slots on the radiating patch. Karmakar *et al.* [369] designed an UWB fractal antenna by introducing Sierpinski carpet fractal structure on the radiating patch and the ground plane for the miniaturization and bandwidth enhancement. The dual band notch characteristics had been introduced by loading the ground plane with two open-ended quarter wavelength L-shaped slots for WiMAX band and two half-wavelength U-shaped slots for IEEE802.11a and HIPERLAN/2 bands.

In 2012, Sawant *et al.* [370] designed an UWB fractal antenna with band notch characteristics by inscribing a square patch inside a circular monopole and loading the feed line with N-shaped slot. Li *et al.* [371] designed two configurations of cantor set fractal UWB antenna with switchable band notch characteristics. The reconfigurable band notch characteristics for the WLAN/WiMAX bands were introduced by loading the CPW ground plane with U-shaped slots in one configuration and inserting T-shaped stub in another configuration along with switches to achieve switchable property. Omar [372] designed a CPW-fed UWB fractal antenna by introducing square shaped Koch-fractals on the sides of an equilateral triangle. The initial length of the side of the triangle was calculated so that the antenna resonates in its TM_{10} mode.

In parallel to this, Kumar and Chaubey [373] designed a CPW-feed UWB fractal antenna for DS-CDMA applications by developing a tree-like fractal structure. Its monostatic RCS was found to be reducing at higher frequencies due to the object size greater than wavelength and vice versa. It had a linear phase.

Kumar and Kokate [374] achieved an UWB bandwidth in a CPW-fed fractal antenna by introducing matching strips in the ground plane inclined at some angle from the centre of the patch. Moghadasi *et al.* [375] enhanced the bandwidth of a fractal-based monopole antenna by using the concept of increasing the unit-cells of the fractal tree resulting in proportional increase in the surface current paths i.e. additional resonances without significantly impacting on the antenna’s physical size to make it suitable for UWB applications. It consists of a radiating patch having repeating pattern of unit-cells to create a fractal tree, and a semicircular ground-plane. An effective impedance matching and return-loss characteristics with linear phase variations had been achieved by utilizing the configuration in which the ground plane surface covers a portion of the tree’s stem or feed line.

Kumar *et al.* [376] designed a tapered microstrip line fed UWB fractal antenna by introducing Giusepe Peano fractal on the edges of a rectangular patch antenna and Sierpinski Carpet fractal in the square patch by loading the patch with circular slots. Karmakar *et al.* [377] achieved band notch characteristics for IEEE 802.11a and HYPERLAN/2) by loading the CPW-fed ice cream cone patch with Hilbert Curve slots and for X-band uplink satellite communication systems by etching two symmetrical Hilbert shaped slots on the ground plane. Kumar *et al.* [378] achieved an UWB bandwidth in a CPW-fed circular patch monopole antenna by inscribing inclined fractal polyhedrons in various concentric circles inside the patch to increase the resonance frequency in higher frequencies.

Ghatak *et al.* [379] designed a CPW-fed circular UWB fractal antenna by inscribing Sierpinski gasket triangular fractal structures inside the circular patch. The band notch function for the WLAN band had been achieved by introducing L-shaped slot on the ground plane. The slots had their one open end which makes them to act as quarter wavelength resonator having infinite impedance at the open end. Due to this the impedance at the feeding point looking into the resonator appears to be short circuited resulting into reflection of excited surface current resulting in reduced radiation at the notch frequency. Gorai *et al.* [380] designed an UWB Sierpinski fractal binomial tapered planar monopole antenna by using equation based binomial tapered patch with Sierpinski carpet fractal structures etched on it and the band over 10.6 GHz had been rejected by using split ring slot. Li *et al.* [381] designed a CPW-fed UWB fractal antenna using Koch fractal shaped patch and rectangular ground plane. Karmakar *et al.* [382] investigated a CPW-fed “Y” shaped UWB fractal antenna by loading the patch with hexagonal slots and the ground plane with Sierpinski Carpet slots.

Cook *et al*. [383-384] designed an inkjet-printed UWB antenna on paper substrate by using tapered Sierpinski Gasket fractal matching network to improve the impedance matching over the entire UWB band. In another configuration, an UWB fractal antenna was designed by applying the iterative function system based complex geometry as a combination of Koch Snowflake fractal and the Sierpinski gasket fractal to a microstrip monopole antenna. Li *et al.* [385] presented a CPW-fed wide slot Cantor set fractal MIMO diversity UWB antenna by using two identical Cantor set fractal radiating patches. Multiple slots were loaded on the CPW ground plane to improve the isolation performance of the antenna.

Kumar and Nikam [386] enhanced the bandwidth of an appollian gasket fractal antenna by modifying the radiator structure and adding two semi-circular metallic surfaces to the rectangular coplanar waveguide ground plane. The radiator structure was modified by loading it with iterative structures, resulting into shifting of lower band edge frequency towards the lower side and enhancing the size of the radiator.

In 2013, Moghadasi *et al.* [387] designed a CPW-fed UWB fractal antenna consisting a tree-like fractal structure as radiating patch and a modified ground plane. The ground plane was modified by curving its upper edge and etching rectangular slots from its sides to improve the impedance matching leading to bandwidth enhancement. The band notch function was achieved by introducing folded T-shaped element on the radiating patch.

Biswas *et al.* [388] designed a microstrip line fed UWB fractal antenna by introducing Sierpinski carpet slots on the circular radiating patch and truncating the rectangular ground plane in steps for improving the impedance matching. The WLAN band-rejection function was realized by introducing half wavelength long U-slots on the ground plane.

Karmakar *et al.* [389] enhanced the bandwidth of a microstrip line fed UWB fractal antenna by introducing steps on the conventional rectangular radiating patch and by loading the rectangular ground plane with fractal slots. Kim *et al.* [390] designed a CPW-fed UWB flower shaped circular fractal monopole antenna by introducing six-petaled flower fractal pattern in the circular radiating patch. Ghatak *et al.* [391] designed a CPW-fed circular UWB fractal antenna by using the concept of Descartes Circle Theorem. The circular radiating patch was loaded with circular fractal slots whose dimensions were calculated by using the Descartes Circle Theorem to miniaturize the antenna size and enhance the impedance bandwidth. The WLAN band notch characteristics were achieved by loading the ground plane with two symmetrical L-shaped slots.

Ghatak *et al.* [392] designed a CPW-fed hexagonal UWB fractal antenna by loading the hexagonal patch with hexagonal Sierpinski Carpet fractal structures up to two iterations to reduce the antenna size and enhance the impedance bandwidth. The band rejection function was introduced by loading the patch with “Y” shaped slot extending into feed line. Kumar and Choubey [393] designed an UWB pentagonal circular fractal antenna by etching twelve pentagonal slots between two concentric circles. The band notch characteristic was realized by introducing ring resonator slot in the CPW feed line.

Kushwaha and Kumar [394] designed an UWB fractal antenna with defected ground plane by inscribing tilted square in a circular patch fed by a tapered microstrip line. The ground plane was loaded with multiple slots and an L-strip was also introduced into the ground plane. For further bandwidth enhancement, three shapes of EBG structures i.e. Mushroom type, Cross hair type and Swastik type were introduced to the antenna by reducing the substrate thickness.

Kumar and Gaikwad [395] designed a nano-arm fractal UWB antenna by using rounded corner CPW ground plane and wheel shaped radiating patch. Fallahi and Atlasbaf [396] designed UWB fractal antenna by adding small polygon shapes to the corners of the antenna radiator to enhance the impedance bandwidth by achieving multi resonance operation in a small area. Iqbal *et al.* [397] designed a CPW fed heptagonal UWB fractal antenna by placing heptagonal geometry in such a manner that heptagonal structures are concentric arrays of equilateral triangles. Jeemon *et al.* [398] designed an UWB multifractal antenna by applying the combination of two techniques i.e. Koch fractal and Sierpinski to a triangular patch antenna.

In 2014, Jalali and Sedghi [399-400] presented an UWB fractal antenna whose radiating patch was composed of two iterations of rectangular unit cells arranged in a specific manner and it was CPW-fed. The bandwidth was enhanced by loading the rectangular plane with rectangular slots and notches. Zarrabi *et al.* [401] presented an UWB monopole antenna with dual band notch characteristics. The band notch characteristics had been introduced by loading the tapered radiating patch with a combination of rectangular slits and semi Minkowski fractal slots. Tripathi *et al.* [402] designed an UWB fractal antenna by using the combination of octagonal patch geometry and Minkowski curve. The bandwidth performance was improved by loading the ground plane with multiple notches and slots. Same authors [403] presented a Minkowski like fractal antenna for UWB by using a radiator generated through an IFS. The wideband performance was achieved due to multiple resonance phenomena of fractal geometry and repetition of similar segments in the radiator. The initial design of the antenna was started by combining similar Minkowski-like structure segments maintaining the symmetry on a conventional rectangular monopole patch antenna. The addition of the Minkowski-like structures increased the effective length of the antenna to operate the antenna in UWB range.

Choukiker and Behera [404] designed a microstrip line fed UWB fractal antenna comprising a modified Sierpinski radiator achieved by applying Hutchison's geometrical transformation algorithm on a square slot and a grooved ground plane. The WLAN band notch characteristic was achieved by loading the feedline with ∩-slot.

Bounif *et al.* [405] investigated four UWB fractal antenna structures. First structure was a simple fractal antenna based on hexagonal geometry. In second structure, an electric-magnetic-electric matrix was used to miniaturize the antenna footprint with little compromise on bandwidth. Remaining two antennas based on serrated structure reduced the surface. First one was an ultra-wide band antenna, whereas the second had WLAN rejection function. Kushwaha *et al.* [406] enhanced the bandwidth and gain of a CPW-fed fractal UWB slot antenna by using a frequency selective surface reflector. The antenna comprised a CPW ground plane loaded with a combination of two elliptical slots perpendicular to each other, a fourth iterative fractal radiator and two step feed line. The initial structure of radiator was designed by intersecting a vertical ellipse with a horizontal ellipse and then loading this structure with another intersecting structure of a vertical and a horizontal ellipse. Shambavi and Alex [407] enhanced the bandwidth of a circular monopole by introducing fourth iterative square slot loaded circular radiator. Mushroom shaped EBG structure was introduced near to the feedline to realize the WLAN band rejection function.

In 2015, Sawant and Kumar [408] proposed a CPW-fed hexagonal fractal antenna for UWB applications by using stepping feedline. The central portion of the radiating patch was loaded with hexagonal slot due to less current density. Thereafter the central slot was surrounded with smaller hexagonal slots and then those surrounding hexagonal slots were surrounded by further reduced dimensional hexagonal slots.

On the other side, Tripathi *et al.* [409] achieved miniaturization and wideband performance of an octagonal antenna by using Sierpinski fractal geometry. Same authors [410] proposed a dual band notched octagonal UWB antenna. The wideband performance was achieved by loading the ground plane with a rectangular notch and by using octagonal radiator. The band notch function for WiMAX was realized by loading the radiator with equation based Minkowski fractal and for band rejection of WLAN band dual C-shaped single split ring resonator (SSRR) notch were etched on either side of feed line.

In the same year, Rajeshkumar and Raghavan [411] designed a microstrip fed U-shaped UWB fractal monopole antenna with enhanced bandwidth and band notched characteristics. The self-similar fractal property is used in the U-shape monopole to obtain 2^n surface current paths to achieve good impedance matching over a wider bandwidth. By etching a novel complementary split ring resonator in the ground plane, the stop bands for wireless local area network and HIPERLAN/2 (5.15–5.825 GHz) systems were obtained.

1.2.3 Dipole Antenna

Thomas *et al.* [412] (1994) presented a planar circular element dipole antenna which provided better performance. In 2001, Schantz and Fullerton [413] designed a diamond dipole by using isosceles triangular elements to form an inverted bowtie antenna. The base and height of the antenna were scaled to $\lambda/4$ at the centre frequency. It had an ultra-wideband, non-time dispersive response and matched input impedance characteristics.

In 2002, Schantz [414] designed UWB dipole antenna by using elliptical elements of different eccentricities. It was found that the matching improves with increasing eccentricity. They had return loss better than -10 dB for minor axis $l_{\lambda} \geq 0.20\lambda$ while the radiation efficiency of more than 50% was observed for $l_{\lambda} \geq 0.14\lambda$. He analyzed the planar elliptical dipole as a pair of opposing slotline horns by using the expressions for slotline impedance and treating the slotline as a 100Ω-377Ω transformer between the feed and a circular boundary, calculating the slot widths by assuming an exponential and a Klopfenstein taper and determining another taper by the analysis of energy flow around an ideal dipole. The combined analysis provided an optimized eccentricity ratio of 1.50:1 of an elliptical dipole. Morrow *et al.* [415] presented a rolled edge UWB dipole antenna derived by rolling the edges of a V-shaped antenna. The edges were rolled to minimize the internal clutter resulting into antenna radiation performance improvement with high directivity.

In 2003, Schantz [416] prevented the antenna pattern distortion and system performance as observed in centre fed elliptical dipole [414] by feeding the elliptical dipole by a balun transformer at the base of the antenna. Lule *et al.* [417] carried out the FDTD analysis of the UWB diamond dipole. Ma and Jeng [418] designed a tapered slot fed UWB dipole antenna having dual advantages i.e. wideband characteristics with endfire patterns of tapered slot antenna and almost omnidirectional patterns in the H-plane of printed dipole antennas.

Ye and Lauber [419] carried out the simulation study of circular and elliptical UWB dipole antenna structures presented by Schantz [414] by using FDTD technique. Kim *et al.* [420] presented a stepped-fat UWB dipole antenna by introducing an additional arm to the conventional fat dipole. The addition of this new arm resulted into additional controlling factors through which the antenna performance can be modified in a better way.

In 2004, Zhen *et al.* [421] carried out the FDTD analysis of two UWB dipole antenna configurations i.e. UWB dipole antenna configuration developed by inscribing a sphere at the base of a cone antenna and another configuration developed from circular disc monopoles. Taguchi *et al.* [422] designed a centre fed resistance-loaded planar dipole antenna within a rectangular parallelepiped cavity. The back radiations had been prevented by placing a conducting plate at the back plane of the cavity. Zhao [423] designed a band notched UWB dipole antenna structure by combining a radiating patch with two additional stubs. The wider central patch contributed mainly in the antenna gain while the other two side stubs or patches coupled to it were providing a frequency band expanding effect.

In 2005, Lule *et al.* [424] derived a diamond shaped dipole antenna for UWB applications from a circular disc by trimming its top part to the shape of a planar inverted cone without affecting the bottom part which acted as the feeding edge. Same authors [425] presented a tear drop shaped UWB dipole antenna loaded with elliptical slot. Horita and Iwasaki [426] presented an asymmetric trapezoid UWB dipole antenna comprising two asymmetric trapezoids as two poles of the dipole. Sevskiy and Wiesbeck [427] investigated H, S, Z, X, Y configurations of log periodic dipole antenna for UWB and multiband operations. Unidirectional, V-shaped, and conical radiation patterns were obtained by using metal plate reflectors. Ma and Jeng [428] presented a detailed study of the antenna[418] with the replacement of curved reflector by a rectangular reflector. The proposed antenna comprised a wide-band tapered slot feeding structure and a pair of curved strips for uniform energy radiation. The antenna’s inband impedance matching had been improved by adding an additional parasitic element in front of the feeding aperture. Wu and Chen [429] carried out the comparison of four dipole antenna configurations for the impedance matching, realized gain, and polarization over the UWB band.

In 2006, Zhang *et al.* [430] designed a microstrip fed planar elliptical UWB dipole antenna comprising trimmed elliptical radiators fed by a microstrip line. Karacolak and Topsakal [431] presented an UWB dipole antenna configuration on two different substrate materials i.e. Rogers RO3006 and Liquid Crystal Polymer (LCP). It comprised radiators in the shape of a rectangular patch having a circular section on one end while a triangular section on the other end and it was fed by a stepped microstrip line. Cerney and Mazanek [432] analyzed four wideband dipole antenna structures for UWB applications i.e. thick dipole, planar bow-tie dipole, planar rhombus dipole, elliptical dipole and diamond dipole. Two configurations of the square dipole antenna were also optimized by using elliptical or semicircular basis in one configuration while the other configuration had triangular basis. Dubrovka and Vasylenko [433] analyzed the effect of the antenna profile at its feeding on the impedance matching and the antenna performance. Three profiles were investigated i.e. exponential, logarithmic and bell shaped. The feeding structure comprised a modified microstrip line, formed by two parallel strips. The antenna consisted two identical printed bows, one on the top and one on the bottom of the substrate material. Park and Song [434] derived a stepped fat UWB dipole antenna from a conventional fat dipole antenna consisting two square monopoles.

In 2007, Li *et al.* [435] designed an UWB dipole antenna for wireless communication by using two C-shaped radiating elements shorted to each other by the use of shorting strips. The use of C-shaped radiator and shorting strips resulted into miniaturization of the antenna size.

Kanaya *et al.* [436] modified a CPW fed standard rectangular slot wideband dipole antenna to derive an UWB slot dipole antenna by loading the CPW ground plane with two rectangular slots. Katsuta and Iwasaki [437] modified the asymmetric trapezoid dipole antenna [426] to introduce an additional band by loading the larger trapezoid with slots and introduced band rejection function by loading the smaller patch with slots.

Horita and Iwasaki [438] presented the effect of patch dimensions on the performance of dipole antenna [426] along with the excited activation mode. The lower resonance frequency was shifted towards lower side and an additional resonance was excited between lower resonance and higher resonance by removing the upper half of both asymmetric trapezoid radiators. Cerny and Mazanek [439-440] carried out the optimization of the dipole antenna dimensions suitable for the UWB applications by using PSO algorithm in MATLAB and CST. Two feeding techniques i.e. guide the feeding signal in the dipole axis, since dipole have zero radiation in the direction of dipole axis and feed the monopole directly by a microstrip line were also presented.

In 2008, Zhang *et al.* [441] extended the dipole antenna structure[430] to derive the microstrip fed semi-elliptical dipole antenna for UWB applications. It was composed of two trimmed semi-elliptical radiation patches and microstrip-slot coupling structure. The antenna structure was miniaturized by cutting the non-radiating portion of the radiator and the band notched characteristics were introduced by loading the upper radiation patch with rectangular slot. Gao *et al.* [442] presented an UWB dipole antenna comprising two microstrip line fed rectangular patches in opposite direction and printed on opposite sides of the substrate. Zhang and Wang [443] presented an UWB dipole antenna having two U-shaped radiators. It had a flat transfer function response as a transmitter but while for the receiver case it decreased beyond 8 GHz due to the out of phase radiation from two edges of the U-shaped arms at those frequencies. Quintero and Skrivervik [444] analyzed four rotated configurations of an elliptical dipole antenna fed by a coplanar stripline. Lee *et al.* [445] put forward a printed circuit board elliptical dipole antenna for UWB applications comprising two elliptical shaped radiators to produce a broad-beamwidth and broad bandwidth with linear polarization. The lower radiator was loaded with an elliptical slot to accommodate microstrip feedline extending into the dipole center or the attached point of the two adjacent elliptical radiators. A broad bandwidth had been achieved by the formation of multiple semi-elliptic thin-line dipoles of varying lengths resulting into excitation of multi-linear modes. Pergol and Zieniutycz [446] presented an UWB dipole antenna having radiator designed by combining a triangle with a trapezium to reduce the size of radiator without affecting the antenna performance. In 2009, same authors [447] sandwiched the circular dipole radiators between two dielectric materials to achieve a size reduction of approximately 20% with an improvement in the return loss.

Tseng and Hsu [448] designed an UWB dipole antenna by using annular ring shaped radiators loaded with rectangular slots for the impedance bandwidth enhancement. The band notched characteristic was introduced by etching four slits on the ground plane. Huang *et al.* [449] modified a conventional bow tie antenna by chiseling two sided-coupled stubs and tuning ground line to reach balanced input to achieve wider bandwidth and ISM band rejection. The radiators were fed by a sectional binomial transformer feedline.

In 2010, Hu *et al.* [450] presented an UWB dipole antenna comprising two trapezoidal patches. The band rejection function was introduced by loading the trapezoidal patches with T-shaped slots.

Sambavi and Alex [451] designed an UWB dipole antenna exhibiting polarization diversity. The radiating structure was designed by the orthogonal combination of five dipole strips of different resonant length. The band notch characteristic was achieved by loading the partial rectangular ground plane with inverted L-shaped slots. Nazli *et al.* [452] improved the characteristics of a printed elliptical UWB dipole antenna by loading the dipole arms with elliptical slots.

In 2011, Nair *et al.* [453] presented a slot fed directive dipole antenna for UWB applications. The upper corners of the rectangular slot line were flared to form two semicircular patches on the same plane. Yu *et al.* [454] designed a printed log periodic dipole antenna (PLPDA) for UWB applications by using ten dipole elements and half mode substrate integrated waveguide (HMSIW) Balun. The bandwidth of the PLPDA got enhanced on increasing the number of dipole elements. Multiple band-notch characteristics for the resonance frequencies were introduced by etching U-shaped slots. Lin *et al.* [455] resolved the feeding problem of dipole antenna by using quasi-microstrip line for transition, which helps into the conversion of a unbalanced transmission line connecting the dipole wafers into a balanced microstrip line resulting into balanced feeding of the antenna. To prevent the impairment of the radiation patterns in case of dipole antenna printed on both sides of the substrate, the two dipole arms were printed on the same side of substrate and one branch of balanced microstrip line was directly connected to one dipole arm, while the other dipole arm was connected with other side's balanced microstrip line through a metal-via-hole on the extended strip.

In 2012, Lin *et al.* [456] carried out the radiation characteristic analysis of an ultra-wideband (UWB) printed dipole antenna with semicircular dipoles by using surface current of the antenna in the equivalent array radiation models of standing wave current at low frequencies and traveling wave current at higher frequencies. Later, Dumoulin *et al.* [457] used square root raised cosine (SRRC) pulse to carry out the time domain analysis of an UWB dipole antenna designed by using Bézier spline shapes. Genetic algorithm was used to refine the Bezier spline shapes to simultaneously take account of both frequency- and time-domain criteria.

In 2013, Khandelwal *et al.* [458] presented a parallel stripline fed log periodic dipole antenna comprising 17 dipole elements of quarter wavelength length. Rolled defective ground plane was used to achieve UWB characteristics. The rectangular feedline is loaded with an U shaped slot to achieve WLAN band notch characteristics.

In 2015, Koziel *et al.* [459] designed a coplanar stripline (CPS) fed dipole antenna with integrated balun by using the surrogate based optimization technique to achieve the final antenna structure at low computational costs and at a high-fidelity level of structure description. Later on, Jung *et al.* [460] designed a planar dipole antenna based on modified Taegeuk structure and achieved a size reduction of 22.8 % in comparison to half wavelength dipole at lower cut off frequency.

From the brief literature survey, it is observed that a lot of work concentrating to the various techniques of enhancing the bandwidth and miniaturization of the microstrip antenna to serve different communication applications has been done on the topic. Still there is a scope to further miniaturize the antenna size with enhanced bandwidth. In view of this, author has endeavored to take up this topic for the investigation. Consequently the details of both simulation and experimental investigations embody the thesis. However, in the following chapter the detailed study of various ultra-wideband microstrip antenna structures are discussed.