CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 Overview of Microstrip Antennas

An antenna may be defined as the structure used for the transformation between a directed wave and a free space wave or vice-versa. While arguing any antenna, one commonly labels its properties as a transmitting antenna. Commencing the reciprocity theorem in antennas one can conclude that the radiation characteristics of receiving antenna is identical to the transmitting antenna provided nonlinear or unilateral devices are not employed with antenna structures. However reciprocity theorem does not guarantee that current distribution on both receiving and transmitting antenna will remain identical.

The idea of microstrip radiators was first introduced by Deschamps [1] in 1953. Developments of microstrip antennas accelerated during 1970s because of availability of various substrates with desired thermal and mechanical properties, advances in photolithography and improved analytical antenna design models. The first practical microstrip antenna was proposed in [3, 4]. Since then practical antenna development continuous efforts are being made to explore various advantages of patch antennas like light weight, low cost, low volume, conformability, compatible with integrated circuits etc. The review of most of the work done initially on microstrip antennas can be found in several references [5-10]. A simple microstrip antenna involves a radiator on unique side of dielectric material and a directing ground plane on the accompanying side. With the availability of flexible substrates it is now also possible to design conformal patch antennas.

1.2 Benefits and Shortcomings of Microstrip Antennas

Microstrip antennas have several benefits over customary microwave antennas over the frequency range from ~100 MHz to ~100 GHz. Some significant gains are low volume, less weight, conformability, inexpensive fabrication for bulk production, easy to accomplish diverse polarizations using antenna feed, multi-frequency operation, easy to incorporate with microwave integrated circuits and easy to manufacture feed lines contained by antenna itself.
These antennas obligate high performance for the reason that enormous quantity of matching elements, power dividers and phase shifters can be added without any cost augmentation. Microstrip array is very dependable since customary antennas may fail at the points of interconnections whereas microstrip antenna whole array is prepared on continuous sheet of copper.

Nevertheless these antennas have some restrictions like contracted bandwidth, lower gain and big ohmic losses in antenna array feed design, generally radiates in partial space, reduced end fire radiations, radiations through feed and intersections, tiny power handling ability, mutual coupling between discrete elements in antenna arrays, elevated levels of cross-polarization and excitation of surface waves in antenna substrates.

1.3 Uses of Microstrip Antennas

With remarkable research being completed on microstrip antennas, nowadays the benefits of microstrip antennas surpasses far more than its shortcomings. Primarily the uses of microstrip antennas were restricted to classifications such as rockets, aircrafts, shrewd weapons, missiles and satellites. In the present day, because of remarkable comfort in manufacture process and accessibility of worthy substrates these antennas find applications in commercial uses [11-12] and are projected to substitute customary antennas in most of uses. The significant uses of microstrip antennas are as follows:

1.3.1 Mobile and Satellite Systems Applications

The practical application of mobile communications involves portable handheld equipment such as pagers, hand telephones, man pack radars, in automobiles like motor cars, vessel navigations and airplanes etc. Patch antenna arrays have also been designed for vehicles accidents minimizing systems, marine radars, altimeters, proximity fuses, telemetry, intruder alarms and secondary surveillance radars. In satellite applications the required beam shaped patterns such as fan beam and sector beam can be easily produced by microstrip antennas thereby decreasing the weight and cost of satellites.

1.3.2 Global Positioning Systems (GPS) Applications

It is expected that several GPS receivers will be used by living beings to determine accurately the positions of motor vehicles, ships and airplanes etc. The GPS has a combination of 24 satellites orbiting around earth every 12 hours at a height of 20,200 Km. A combination of
any four satellites are used to determine the position of an object with precision. The required receiving antennas need to be circularly polarized, low gain and small size operating at L-Band. Hence some patch antennas with all mentioned requirements has been designed for GPS applications and are found to be most suitable.

1.3.3 Direct to Home (DTH) Applications
DTH has been providing television services to people at large. A traditional parabolic antenna is used as a receiver wherein the gain of about 33 dB is required at 11.5 GHz-12 GHz frequency range. However, this antenna is not only bulky but suffers severely from environmental causations like rain and snow. Hence, patch antennas arrays are a suitable replacement because these antennas take less space and even can be hanged on walls of building, less effected by environmental factors and cheap as compared to traditional parabolic antennas.

1.3.4 Patch Antenna Applications in Medicine
Exposure to microwave radiations in medical area can cause hyperthermia while treating infectious tumor. Hence the radiator used in treatment must be conformal to the surface, light weight and easy to handle. Earlier traditional radiators were used in medical fields but now flexible microstrip radiators have offered a suitable choice. The applications of microstrip antennas mentioned here are not at all complete because advantages continue to grow with time.

1.4 Different Microstrip Antennas Configurations
A comprehensive list of various microstrip antennas being used is given in some references [8]. Microstrip antennas have a large number of variable parameters then that of conventional antennas. Broadly speaking microstrip antennas may be categorized into microstrip patch antenna, microstrip slot antenna, microstrip dipoles and microstrip travelling wave antennas.

1.4.1 Microstrip Patch Antenna (MPA)
MPA consists of a conducting patch of some flat or non-flat geometry on any side of substrate. A conducting ground plane is used on the opposite side of a substrate. Usually a patch antenna has a gain around 5 dB and 3-dB beam width around 70°-90°. Commonly used patch geometries are rectangle, triangle, ellipse, ring and disk however other geometries are
also used like elliptical ring, semi ring, ring-sector, pentagon, hexagonal with inner circle, eccentric circular ring H-shape, U-shape, L-shape, rectangular ring, rectangular ring with inner circle, isosceles triangle, cross-junction, T-shape and trapezoidal etc. Radiations phenomenon in patch antennas is due to fringing fields generated amid the edges of patch and ground plane. A simple co-axial feed antenna is shown in Figure 1.1.

![Figure 1.1: Upper view and cross view of a co-axial feed microstrip antenna (From [9], © Artech house, 2003).]

1.4.2 Microstrip Slot Antennas
Produced slot antennas have a space in the ground plane backed by dielectric substrate. The slot may be a printed slot, rectangular slot, annular slot, tapered slot or annular ring slot. These antennas can be microstrip feed or CPW feed and have a bidirectional radiation pattern but with a reflector it can be made unidirectional. A combination of strips and slots helps in achieving a circular polarized antenna. Printed slot antennas can produces end fire radiation pattern, wide bandwidth and low cross polarization which is not possible in microstrip patch antenna.

1.4.3 Microstrip Travelling wave Antennas
These antennas consist of a long microstrip periodic structure terminated with resistive loads to suppress standing waves. The width of microstrip should be enough to support Transverse Electric modes. These antennas can be designed such that the main lobe can be moved in some direction from the broadside to end-fire.
1.5 Feeding Methods in MPA

The five most repeatedly used feeding practices in antenna scheme are coaxial feed, microstrip line, aperture coupling, proximity coupling and co-planar waveguide feed.

1.5.1 Co-axial Feeding

The inner conductor of coaxial cable touches the patch via a slot in substrate and ground plane to transfer power. The location of feed point is selected so as to have a best impedance matching. The advantages of co-axial feed are that the inner conductor can be positioned at any preferred location on the patch so as to have an impedance match. The disadvantage of this type of feed is that it requires large number of soldering joints hence making the antenna non-planar. For thick substrates the height of inner conductor increases thereby making the input impedance more inductive in nature and cause impedance mismatch. Furthermore, it gives narrow bandwidth for thicker antenna substrate and it is considerably difficult to model thick co-axial feed substrates (h>0.02λ0).

1.5.2 Microstrip Line Feed

The benefit of this style of feeding mechanism is patch as well as feed is fabricated simultaneously on the same substrate thus the antenna remains planar as shown in Figure 1.2(a). The disadvantage in edge-feed is that for impedance matching a quarter wave transformer or similar structure is used thereby the length of feed increases to the size of patch and causing undesired radiations with increased cross-polar level. The gap-coupled feed has a narrow gap between patch and feed and therefore has limitations on power handling capability of antenna. Moreover, the bandwidth achieved using this type of feed for practical designs is 2-5%.

1.5.3 Proximity Coupling

The substrate used here is of two layers as shown in Figure 1.2(b) where patch is on the upper layer and feed comes on the lower layer. The advantages of this type of feed [13-14] are elimination of undesired radiations which are prominent in microstrip line feed case. This type of feed gives increased bandwidth due to increase in substrate thickness. The disadvantages of this technique are increased antenna size due to thicker substrate and alignment of two substrate layers and hence antenna fabrication becomes tedious.
1.5.4 Aperture Coupling

The advantages of this feeding technique are wider bandwidth and shielding of patch antenna from unwanted radiations from feed structure thus maintaining polarization purity [15]. In this coupling the field of feed is interacted with the patch through a slot in the ground plane as illustrated in Figure 1.2(c). The bandwidth obtained is around 12%. Impedance matching can be accomplished by adjusting the measurement of feed line and size of slot used in the ground plane. The substrate used for the feed line should have high dielectric constant and should be thin. In depth analysis of this type of feeding technique can be found in references [16-18]. The fabrication of antenna using this type of feeding mechanism is difficult.

1.5.5 Coplanar Waveguide (CPW) Feed

Coplanar waveguide (CPW) feeding technique is shown in Figure 1.2(d) [19]. The CPW line is scratched on the conducting ground plane of MPA and coupling is achieved using a slot. The advantages with this feed are that the radiations from feed structure are negligible as radiation from both CPW slots is out of phase. The major disadvantage of this type of feed are high radiation from the etched slot thereby decreasing the front to back ratio. However, front to back ratio can be improved by means of a circular loop [20]. A summary of all the feeding techniques discussed is presented in Table 1.1.

Table 1.1: Comparison of various feed structures in microstrip patch antenna (From [7], © Artech house, 2001)

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<th>Feed types in Antenna design</th>
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Figure 1.2: Rectangular patch feed by (a) Microstrip feed, (b) Electromagnetic coupling, (c) aperture coupling, (d) Coplanar Waveguide (CPW) (From [9], © Artech house, 2003).
1.6 Analysis of Microstrip Antennas

The analysis of antenna helps to predict the radiation pattern, gain, mutual coupling, polarization, impedance bandwidth and antenna efficiency etc. There are two approaches to analyze the patch antenna. First approach deals with equivalent Magnetic current distribution around the patch antenna edges. Following methods are included under first approach:

1. The transmission Line Model
2. The cavity Model
3. The Multiport Network Model

Second approach deals with electric current spreading on the conducting patch and ground similar to traditional dipole antennas. Following methods are included under second approach:

1. The Method of Moments (MoM)
2. The Finite Element Method (FEM)
3. The Spectral domain Technique (SDT)

1.6.1 The Transmission Line Model

This model was the first model to analyze the rectangular patch antenna [8]. As, rectangular and square patches originated from microstrip transmission line hence can be modelled in terms of two narrow radiating slots which are separated by a part of transmission line [21-23]. The fields at the edges of patch undergo fringing and it must have to be taken in account because it affects the resonant frequency. This method is easy to apply but most of the antenna configurations cannot be analysed with it.

1.6.2 The Cavity Model

In this model [24-27] the region among conducting patch and ground plane is assumed to work as a cavity that is formed by magnetic walls on the sides to simulate open circuits and electric walls on the top and bottom surfaces. When the patch antenna is excited the charge is induced on the exterior and interior layer of patch and on the ground plane. Due to small thickness of substrates the attractive mechanism between the charges dominates the repulsive mechanism and current flow over the exterior patch surface is negligible and ideally
tangential component of magnetic field is zero. The far field and equivalent power radiated is calculated by magnetic currents on side walls of the cavity.

1.6.3 The Multiport Network Model (MNM)
In this model [28] fields below the patch and exterior the patch are modelled distinctly. The conducting patch is modelled as a planar layout with various ports around its edges. The length of port is small enough so that electromagnetic field over it remains constant. Green’s functions used to calculate the impedance matrix of patch. The patch area is increased outward so as to take into account the fringing fields. The impedance matrix is combined using segmentation method and a voltage distribution around the edges of patch is obtained. All three methods discussed above uses magnetic current distribution around patch edges which is obtained from analogues voltage distribution to model radiation from the patch antennas. These methods are accurate up to a large extent for rectangular patch geometry but not suitable for most of arbitrary radiating elements. Hence for complex shapes other methods explained below are used.

1.6.4 Method of Moments (MoM)
In MoM [29], the radiating patch is analysed in terms of surface currents and dielectric fields are modelled using polarization currents. Then integral equations are framed for the unspecified currents on radiator and its image on ground plane. These integral equalities are then converted into algebraic form so that these can be simulated easily. MoM also takes into fringing fields and thus accuracy increases. Softwares like IE3D and ADS are based on Method of Moments.

1.6.5 Finite Element Method (FEM)
The FEM [30] is more appropriate for volumetric designs unlike MoM which is more suitable for planar designs. Technique used here is division of complete structure into number of small surfaces which may be planar or volumetric surfaces for planar and volumetric structures analysis respectively. The small units are named as planar elements and may be of any shape also known as finite elements. The shapes may be triangular for planar structures and tetrahedral and prism shaped for 3-D configurations or curved geometries. The integration of some basis functions is performed over the antenna by dividing it into small sections. This
method gives advantages in analyzing partial differentiation equations over complex domains of varied precisions.

**1.6.6 Spectral Domain Technique (SDT)**
In this technique a 2-D Fourier transforms along two perpendicular directions in substrate’s plane is employed. After it boundary conditions are used in Fourier transformed plane. The current which is spread over the patch is extended in expressions of basis functions. The matrix equation obtained is then simplified to find electric current on patch and magnetic current over peripheral substrate. The antenna parameters are then evaluated using [31].

**1.6.7 The Finite-Difference Time Domain (FDTD) Method**
The FDTD method [7] has the advantage that it can predict the antenna response over a wide bandwidth in a single sweep as analysis is carried out in time domain. It can take into account various structural in-homogeneities found in antenna structures. Mathematically this method involves direct implementation of Maxwell equations and therefore less approximation is involved. Different category of materials like lossy dielectrics, anisotropic plasmas and magnetized ferrites can be analysed using this method. The unbounded medium used in simulation is bounded by terminating it with absorbers so that reflections can be avoided. The physical space is divided into small cuboids and time domain is also discretized. The wave is launched into the structure and processed to know about the frequency domain and time domain behavior of the structures.

**1.7 Introduction to Metamaterials**
In 1898 Jagdish Chandra Bose conducted research and became the first person to find artificial chiral structures [32]. Researchers in [33-34] made first attempts to artificially tailor the refractive index of any medium. Later, the artificial materials that show some novel responses which do not occur in nature are under continuous research. Metamaterials are artificial materials aimed to interact with and control electromagnetic waves. If any electromagnetic wave interacts with another composite medium it induces electric and magnetic moments thereby significantly disturbing the actual permittivity and permeability of that medium. A large degree of freedom exists with metamaterial engineer in terms of size, shape, composition, density, arrangement and alignment of incorporations. The shape of incorporations in any medium to control its properties is new insight in the metamaterial
processing. Complex materials include a class of materials which have negative real values of permittivity and permeability at some frequencies. In [35] plain wave transmission in a medium where both permittivity and permeability values are negative is shown. Several terms have been associated with metamaterials such as media with negative refractive index, backward wave media, double negative type metamaterials and left-handed media.

Figure 1.3: Materials classifications (From [36], © IEEE press 2006).

The response of a system to incident EM waves is largely determined by the factors of materials involved. These factors are classified generally by two parameters permittivity $\varepsilon$ and permeability $\mu$. Any medium with values of both permittivity and permeability values positive is called as Double Positive (DPS) Medium. Most of dielectrics are examples of DPS materials. Mediums with permittivity values negative and permeability values positive is called epsilon-negative (ENG) medium. The suitable examples in this category include plasmas and metals like silver and gold in infrared and visible frequency range. Any medium with permittivity positive and permeability negative is called as mu-negative (MNG) medium. Gyrotropic materials are examples under this category. If any material have both permittivity and permeability values as negative is called double negative (DNG) medium as classified in Figure 1.3[36].This characteristics of DNG medium can only be obtained from artificial materials. These Left-handed medium allows EM wave propagation through them but phase velocity of propagating waves in this medium is opposite to that of pointing vector. Hence the term negative refractive index [36-38], Left-handed media and Backward Wave Media (BWM) [39] is usually associated with DNG metamaterials [40]. Negative refraction is
usually associated with left handed materials. All materials properties like permittivity and permeability are frequency dependent. Magnetic fields of EM wave are usually lesser than electric fields by intrinsic impedance of the propagating medium. Hence, focus is usually on the electric field, electron motion around the nucleus and basic dipole moment. This gives the idea of electric susceptibility and hence permittivity. However for those media in which magnetic field is dominant one has to focus on magnetic dipoles formed due to current loop. This gives the idea of magnetic susceptibility and hence its permeability. A metamaterial using conducting wires and split-ring resonators (SRR) introduced in [39] proved the existence of negative refractive index over some frequencies. Here conducting wires help in achieving negative permittivity and SRR helps in achieving negative permeability. The applications of these metamaterials can be used with [41-44]. Furthermore, interesting novel properties are obtained when one type of metamaterials are paired with oppositely signed metamaterials like DNG is paired with DPS and ENG with MNG. To characterize these metamaterials a modification of standard free-space model which involves transmission and reflection coefficient measurements of a sample when illuminated by EM wave from a directive antenna can be used. It should be noted that large slabs are used to avoid diffraction at edges and therefore the task of manufacturing metamaterials with large number of periodic inclusions has become tedious. Experimental characterizations of Single Negative (SNG) medium and DNG are performed [45-46] in a scattering chamber. The metamaterial is surrounded by EM wave absorber and contained in metallic box. A TE mode if launched into this due to small thickness of chamber standing waves will not excite. Also, EM wave absorbers prevent modes in horizontal direction. The top and bottom of the box impose periodic boundary conditions and whole setup appears if a TEM wave influences the infinite metamaterial at normal incidence. The other metamaterial testing method used is waveguide method. In this method the environment is completely closed, diffraction is absent and experimental set up size is small.

1.8 Evolution of Electromagnetic Band Gap (EBG) Structures

1.8.1 Defected Ground Structures (DGS)
DGS is an engraved shape that generally exists on the backside of conducting ground planes. It is one of the progressive areas of research in recent times. It is simple to fabricate and found greater applications in filters, antennas, oscillators and amplifiers. DGS has become quite
popular in filter designs [47] with good pass band and band reject response with good selectivity and ripple rejections. The basic DGS element is a slot in the ground plane placed directly beneath the microstrip feed as shown in Figure 1.4. Different shapes of DGS have been proposed like rectangle [48-49], square [50], circle [51-52], dumbbell [53-56], spiral [57], L-shaped [58], U-Shaped, V-shaped [59-60], hexagonal shaped [61], hairpin shaped [62-63], concentric-ring shaped [64], cross-shaped [65], combinations of different shapes [66-67] and periodic DGS forms [68-69]. Each shape differs in terms of electrical parameters, higher-order response, L-C equivalent circuit, coupling coefficient and band gap etc.

![Figure 1.4: Different geometries of DGS structures with microstrip line.](image)

The equivalent value of Land C in the equivalent circuit is determined by the dimension of DGS structure and its alignment relative to transmission line. The most common application of DGS in antennas is to reduce the mutual coupling among the antennas, power amplifiers [70-71], dividers [72-73], harmonic reduction [74-75] and cross-polarization reduction [76] in patch antennas, couplers, oscillators, transmission lines, filters and combiners [73]. DGS also find applications in delay lines, it does not affect odd mode transmission but slows down the even mode propagation thus creating a kind of slow wave structure. The disadvantages of DGS structures are that it radiates as it behaves like a slot antenna. Although at the resonance of DGS most of the energy is reflected to the transmission line even then radiations from the slot cannot be ignored. The DGS has advantages over Photonic Band Gap (PBG) such as small area requirement, simple fabrication with high precision and needs less circuit size to obtain slow-wave effect [77].

1.8.2 Photonic Band Gap (PBG) Structures
PBG arrangements may comprise 1D, 2D and 3D periodic arrangements which performs considerable like a band-stop filter, discontinues promulgation of waves at certain frequencies. These may have two groupings either of two dissimilar dielectric constituents or one metal and one dielectric substance. However, combinations of two different dielectric
materials are more common as metallic loss can be avoided here which is prominent at high frequencies. Dielectric materials required to make PBG structures are now extensively available for complete frequency range from ultraviolet to microwave range. Many characteristics of basic crystals and photonic crystals are common, in fact some of the properties of photonic crystals are inspired from ordinary crystals. The major difference between these crystals is the scale of lattice constant, while this scale is in angstrom in ordinary crystals its value becomes in millimeters in photonic crystals. Various configurations of PBG structures for different applications are shown in Figure 1.5.

![Figure 1.5: Different PBG configurations (From [78], © Hindawi 2013).](image)

Different technologies have been developed in recent years to manufacture 2D and 3D PBG structures. Practical design of 2D PBG structures includes a 2D PBG slab of finite thickness with a Perfect Electric Conductor (PEC) around its periphery. In optical technology PBG can be formed by combining Materials of two different dielectric constants [79]. PBGs are usually analysed in terms of unit cell which may be defined as a homogenous solid which when repeated in 3D with fixed distance forms the complete crystal. The band gap in PBGs is heavily dependent on lattice constant of crystals, refractive index of dielectrics used and impurities in the crystal. The concepts of PBGs are also used with the microstrip patch antennas and tubular air holes are decorated into the substrate of antenna. This defect in substrate helps in minimizing the undesired surface waves in patch antenna. It improves bandwidth, reduces side lobes, increases directivity and minimizes coupling which are common concerns for patch antennas. The substrate under patch is not patterned so as to avoid the alteration in resonant frequency.

### 1.8.3 Electromagnetic Band Gap (EBG) Structures

The name Electromagnetic band gap structure, EBG was first coined by Prof. E.Yablonovitch with his research group in 1996 [80-81]. EBGs resemble closely to photonic band gap
structures PBGs [82-83] which are frequently used at microwave frequencies. Incident waves analysis on impedance surfaces was shown in [84-85] thereby helping in development of EBG design. EBGs can be seen as revamped corrugated structures [85]. Artificially soft and hard surfaces in electromagnetics [86] in early 90s also show some traces of EBGs. Actually, EBGs origin can be related to Frequency Selective Surfaces (FSS), which was a fully grown technology with applications in defense sector mainly in EM wave absorbers and stealth applications [87-89]. Ph.D. dissertation submitted to University of California in 1999 by D. Sievenpiper [80] led to a large number of publications and patents related to integration of EBGs with antennas. Sievenpiper emphasized the practice of EBGs in destroying surface waves in a specified band gap. The reflection phase coefficient to the incident influences on EBG structures in this band is nearby zero. EBGs application with monopoles, satellite communications and human head shielding from cellular radiations was also shown.

1.9 Different Analysis Methods for EBGs

EBG structures analysis can be done by three methods namely lumped circuit model, transmission line model and full wave numerical analysis models. The lumped analysis model is simplest of all and it describes the EBG structures in terms of equivalent inductance and capacitance and therefore helps in determining the band gap. This model is not very accurate as approximations of EBG structures in terms of L and C is not precise. Transmission line method as reported in [90] and floquet boundary conditions are used in this approach. The cascaded transmission line which contains periodic impedance and coupling capacitance is then analysed and a dispersion curve is obtained. This model provides more information than the lumped circuit model. The propagating surface wave’s different modes, band gaps and left and right handed regions can be obtained easily from dispersion curve. The limitations with this method are also to obtain equivalent impedance and coupling capacitance values. Although for some simple geometries approximations are found to be accurate but this is not true for all geometries. With continuous research frequency domain based methods like Method of Moments (MoM) and Finite Element Method (FEM) and time domain methods like Finite Difference Time Domain (FDTD) has been developed recently. The advantages with full wave analysis methods like FDTD are accuracy and changeability. Other advantages with FDTD model include calculations of various parameters of EBGs like surface impedance, reflection phase and dispersion diagrams for different geometries.
1.10 FDTD Analysis Method for Periodic Structures

The fundamental goal of many antenna problems is to compute using basic Maxwell equations with different boundary conditions. Due to fast computers available today many different methods for computations are proposed in [91] based on either integral form or differential forms of Maxwell’s equations. These equations can be solved in both frequency and time domains. FDTD uses the time and space formats [92] while solving the Maxwell’s equations for a broad range of antenna related structures. Fourier transformation of the time domain data is taken to obtain desired wide band frequency response. This method also gives the advantage of providing a wide band frequency response in a single simulation sweep. It is due to advantages of FDTD that it is being used from traditional electromagnetic problems to recent one like human head interaction with mobile phone radiations etc.

1.10.1 Yee’s Cell and Concept of Boundary Conditions

FDTD method starts with the differential format of Maxwell’s equations:

\[ \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}, \nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}, \nabla \cdot \vec{D} = \rho \quad \text{and} \quad \nabla \cdot \vec{B} = 0 \quad \cdots (1.1) \]

Where \( \vec{E} \) is the electric field intensity in volt per meter, \( \vec{H} \) is the magnetic field intensity in amperes per meters, \( \vec{B} \) is magnetic flux density in weber per meter, \( \vec{D} \) is the electric flux density in coulombs per meter square, \( \vec{J} \) is the electric current density in ampere per meter square, \( \rho \) is the charge density in coulombs per cubic meters. Also,

\[ \vec{D} = \varepsilon \vec{E}, \vec{B} = \mu \vec{H} \quad \text{and} \quad \vec{J} = \sigma \vec{E} \quad \cdots (1.2) \]

Where, \( \varepsilon \) is permittivity, \( \mu \) is permeability and \( \sigma \) is the conductivity of the medium. The Maxwell’s equations can be solved numerically using Yee’s cubic lattice [93]. The dimensions of lattice are \((\Delta x, \Delta y, \Delta z)\) in rectangular co-ordinates. The space domain is then formed by these small cubic lattices with grid point \((i, j, k)\) is given as:

\[ (i, j, k) = (i\Delta x, j\Delta y, k\Delta z) \quad \cdots (1.3) \]

Figure 1.6 shows that electric fields are taken at the middle of cell and magnetic fields are present at the corners [94]. Each electric fields component has four magnetic fields components around it and similarly each magnetic field component has four electric field components around it.
The difference between calculations of electric and magnetic fields is half step. If electric field is calculated at \( t = n\Delta t \) then magnetic field will be calculated at \( t = \left(n + \frac{1}{2}\right)\Delta t \). The following components are also present on lattice and are used in the computations:

\[
\begin{align*}
E_n^{\pm1/2} & , E_n^{0}, E_n^{\pm1/2} & , H_n^{0}, H_n^{\pm1/2} & , H_n^{0}, H_n^{\pm1/2} \quad \ldots (1.4)
\end{align*}
\]

The following six equations are used for free space Yee’s lattice:

\[
\begin{align*}
H_{x,i,j,k-1/2}^{n+1/2} &= H_{x,i,j,k-1/2}^{n-1/2} - \frac{\Delta t}{\mu_0} \left[ \frac{E_{y,i,j,k-1/2}^n - E_{y,i,j-1/2,k}^n}{\Delta y} - \frac{E_{y,i,j,k-1/2}^n - E_{y,i,j-1/2,k}^n}{\Delta z} \right] \quad \ldots (1.5)
\end{align*}
\]

\[
\begin{align*}
H_{y,i-1/2,j,k}^{n+1/2} &= H_{y,i-1/2,j,k}^{n-1/2} - \frac{\Delta t}{\mu_0} \left[ \frac{E_{z,i,j,k-1/2}^n - E_{z,i-1/2,j,k}^n}{\Delta z} - \frac{E_{z,i,j,k-1/2}^n - E_{z,i-1/2,j,k}^n}{\Delta x} \right] \quad \ldots (1.6)
\end{align*}
\]

\[
\begin{align*}
H_{z,i,j-1/2,k}^{n+1/2} &= H_{z,i,j-1/2,k}^{n-1/2} - \frac{\Delta t}{\mu_0} \left[ \frac{E_{x,i,j,k-1/2}^n - E_{x,i-1/2,j,k}^n}{\Delta x} - \frac{E_{x,i,j,k-1/2}^n - E_{x,i-1/2,j,k}^n}{\Delta y} \right] \quad \ldots (1.7)
\end{align*}
\]
In FDTD simulations the equations (1.5-1.10) are easily modified for different types of available objects like lumped elements [95], dielectrics, conductors and wires etc. Non-linear elements can also be easily analysed using FDTD. The electric and magnetic fields of equations (1.5-1.10) is assigned zero value at \( t = 0 \). A lumped voltage source is then used to excite the antenna at location \((i_0, j_0, k_0)\). The values of magnetic fields are calculated at \( t = n \Delta t + \frac{1}{2} \Delta t \) and electric field values are calculated at \( t = (n+1) \Delta t \). This process is repeated till the desired response is obtained by storing the intermediate results at the grid points. In case of antennas time response moves towards zero value as time increases as all energy radiated to infinity. Lastly, Fourier transform is used to obtain frequency domain characteristics. Matrix inversion is a complex process involved in MoM and can lead to erroneous results that are avoided in FDTD analysis. In order to avoid instability in calculations the time step size \( \Delta t \) must follow the relation given in equation (1.11) with lattice space increments \((\Delta x, \Delta y, \Delta z)\).

\[
\Delta t \leq \frac{1}{c \sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}} \quad \ldots (1.11)
\]

Where \( c \) is the speed of light, some modified FDTD algorithms are also proposed in [96-97] to lessen the above mentioned time constraint. However they require modifications in equations (1.5-1.10). In antennas the radiations theoretically extends till infinity but due to some computational limits of the simulator the computational space has to be restricted. Hence absorbing boundary conditions are used for this [98]. Usually, Perfect Matched Layers (PML) is used to absorb the EM waves without considerable reflections. A voltage source is used for antenna excitation at its feed point. Co-axial feed model and microstrip feed models are also given in [99]. Although distributed sources in which the excitation is on the surface
has also been proposed. The excitation signal used in both the techniques should be properly selected. One of the most commonly used signals is Gaussian wave in modulated form as shown in equation (1.12).

\[ f(t) = \exp \left[ -\frac{(t-t_0)^2}{2\sigma_t^2} \right] \cos \left( 2\pi f_0 t \right) \] … (1.12)

The parameters for the above equation are time delay \( t_0 \), wave width \( \sigma_t \) and centre frequency \( f_0 \). The value of \( t_0 \) lies between \( 3\sigma_t \) to \( 5\sigma_t \). A small value of \( \sigma_t \) means narrow bandwidth wave in time domain and wider bandwidth signal in frequency domain. After FDTD simulations parameters are extracted to know the behavior of different structures like for antennas radiation pattern and input impedance is required and for filters transmission and reflection coefficients are important. In certain applications the periodic EM structure itself extends up to infinity like in waveguides, EBG structures and DNG materials. In this situation PML is of no significance and a new boundary condition known as Periodic boundary condition (PBC) is used. With the use of PBC only a single unit cell is required so as to characterize the behavior of whole structure. These boundary conditions are defined with floquet theory [100].

1.11 Band Gap Determination Methods of EBG Structures

As discussed in previous section that for large periodic EBG structures FDTD analysis takes a longer time in computations and thereby requires extensive memory space. With the introduction of PBCs the calculations and memory requirements are minimized. PBCs are used around the four walls of unit cell of a periodic structure which in turn is equivalent to infinite periodic arrangement of unit cells. Hence with this efficient approach following two methods have been used in band gap calculations.

1.11.1 Dispersion Diagram Method

As we know \( \beta = k \) in a lossless medium, where \( \beta \) is phase constant and \( k \) is wave number.

Phase constant the group velocity \( (u_g) \) and phase velocity \( (u_p) \) can be obtained as [101]:

\[ u_p = \frac{\omega}{\beta}, u_g = \frac{d\omega}{d\beta} \] … (1.13)

\( \beta \) is linearly related with frequency \( \omega \) as:
\[ \beta(\omega) = k = \omega \sqrt{\left(\varepsilon_0 \mu_0\right)} \]  

… (1.14)

For a propagating surface waves in the dielectric substrates of antennas no direct formulation is available to find the value of wave number \( k \). Hence to find \( k \) either Eigen-mode solver is used or full wave analysis is to be carried out. The solution of Eigen mode solver can give different propagating modes at a particular frequency. Hence a diagram among \( \beta \) and \( k \) is planned with each circulating mode having dissimilar phase velocity, group velocity and fields vectors is known as dispersion diagram. For EBG structures the propagating surface wave’s field distribution is also periodic with delay calculated by \( k \) and period \((p)\). Every propagating surface waves can be decomposed into infinite series of harmonics with different group velocities but same phase velocities as:

\[ E(x, y, z) = \sum_{n=\infty}^{n=\infty} E_n(y, z) e^{-jk_{x_n}x} \quad \text{and} \quad K_{xn}(\omega) = K_x(\omega) + n \frac{2\pi}{p} \]  

… (1.15)

A single harmonic cannot satisfy the boundary condition but a group of these harmonics satisfy the boundary conditions and these groups denote a mode. Dispersion relation \( K_x(\omega) \) is periodic with a period of \( \frac{2\pi}{p} \) [102] along \( k \) axis. Hence this relation is plotted only for one period namely \( 0 \leq K_{xn} \leq \frac{2\pi}{p} \) period so as to know the complete behavior of periodic structures.

For 2-D periodic structures the 2-D brillouin area is usually defined as:

\[ 0 \leq K_{xn} \leq \frac{2\pi}{p_x} \quad \text{and} \quad 0 \leq K_{yn} \leq \frac{2\pi}{p_y} \]  

… (1.16)

The mode 1 in the dispersion diagram usually starts at zero frequency, the Eigen-frequency firstly increases with wave-number and then decreases. There exist certain band gap between different propagating modes also known as surface wave band gap and propagation of surface waves is prohibited inside this band gap of EBG structures.

### 1.1.1.2 Reflection Phase Method for Plane wave Incidence

EBG structures also show an interesting property of reflection phase which helps in determining the band gap of EBG structures. Reflection phase is defined as the relation of reflected wave to incident wave at the reflecting structure. If a wave is incident on a simple ground plane it is reflected entirely thus giving the value of reflection coefficient magnitude
as unity. In other words, if a plane wave is incident on the Perfect Electric Conductor (PEC), the boundary condition i.e. the tangential component of electric field is zero must be satisfied. Hence the incident and reflected waves are out of phase giving a reflection coefficient of -1 or reflection phase of 180°. However in case of Perfect Magnetic conductors (PMC) the incident electric field and reflected electric fields have same signs and incident and reflected magnetic fields have opposite signs. This gives reflection coefficient value equals to +1 or a reflection phase of 0°. Normally PMC structures does not occur in nature. However research done with EBG structures that reveals that these structures can act like PMC in a specified frequency band. Reflection phase from EBG cell diverges from 180° to -180° with frequency. It is due to this reflection phase characteristics that EBG structures have been used with Low-profile wire antennas. A unit cell model is used for calculations of reflection phase at plane wave normal incidence [103]. The unit cell of EBG structures is surrounded with PBCs so as to make it equivalent to infinite periodic structure. The (Perfect Matched Layer) PML is placed at the top of the box at a distance of approximately 0.55λ so as to absorb the reflected waves. The observation plane to monitor the reflected waves is taken at a height of 0.50λ from EBG unit cell. It is because at the EBG structures high order harmonics occurs and it may affect the results negatively. The normalized reflected phase from EBG structures is calculated as

\[ \phi = \phi^{EBG} - \phi^{PEC} + \pi \]  

(1.17)

By implementing equation (1.17) the propagation phase due to distance between the EBG surface and observation plane is removed. \( \pi \) is added in the equation to account for the phase added due to PEC surface. The same method is also used while experimentally measuring the phase of reflected waves. The split field FDTD method shown in [104] may be used to determine the reflection phase of plane waves in case of oblique incidence. The reflection phase also helps in determining the band gap of EBG structures and in the band gap the phase varies from +90° to -90°.

### 1.12 Literature Review of EBG Structures

In late 1990s the uniplanar EBG structures [105] were developed. Later, these different shapes of EBG structures were reported and a comparison among them was shown [106]. In [107] soft and hard characteristics of EBG structure for TE and TM propagating modes is shown. In [108] a comparison of bandgap characteristics among EBGs and soft surfaces is made. In [109] relationship between EBG and right/left handed structures is shown.
structures have some limits which are discussed in [110]. New configurations of EBG structures are proposed like dumbbell shaped [111], cylindrical and ellipse shaped [112] and double armed [113] etc. In [114] Low –Temperature Co-fired Ceramic (LTCC) is used for EBG fabrications. In [115-116] multi-layered EBG structures are discussed. Frequency Selective Surfaces (FSS) were commonly used periodic structures and led to several EBG structure designs [117-118].

Single band-gap to multi-band-gap EBG structures are proposed in [119-120]. Due to rapid surge in EBG structure’s uses compact EBGs are proposed by researchers in [121-122]. Different methods used to realize compactness comprised spiral fashioned EBGs [122-123], by means of Hilbert curve [124] and complementary proposals [125]. EBG cells that have polarization-dependent reflection phase are conversed in [126]. Tunable EBG structures with varactor diodes and added active components are recommended in [127-128]. EBG structure optimization procedures like genetic algorithms [129] and particle swarm optimization [122] are defined so as to analyze these structures effortlessly.

1.12.1 Applications of EBG Structures in Efficient Microstrip Antenna Design
Due to certain interesting properties of EBG structures these are now widely used with antenna and microwave circuits to make them efficient. Review papers related to the applications of EBG structures with microwave and antenna circuits can be found in [130]. EBG structures have found enormous applications to minimize the propagation of surface waves [131-137] in antenna substrates thereby increasing antenna gain and efficiency and reducing back lobes. In [138-139] the enhancement in antenna bandwidth is reported with the application of EBG structures. These structures also have applications in antenna size reduction [140] and improvement in antenna radiation pattern [141]. EBGs have also been used with antenna arrays primarily to minimize the mutual coupling [142-148], which is major cause for reduced antenna efficiency and scan blindness.

1.12.2 EBG Structures Applications with Wire and Slot Antennas
Next important uses of EBG structures are included in low profile wire antennas. In the band gap of EBG structure due to zero reflection phases the radiation characteristics of antenna near EBG ground plane is significantly improved [149-150]. Figure 1.7 shows a simple dipole antenna placed above both PEC and EBG ground planes. Figure 1.8 shows the return loss versus frequency plot for both the ground planes [103]. It can be seen that when the PEC is
used as a ground plane the magnitude of return loss is around 3.5 dB. The poor value of return loss is due to radiations from dipoles are cancelled by the image current of the ground plane.

![Figure 1.7: A dipole over (a) Conventional Ground, (b) EBGs based ground plane (from [103], © IEEE 2003).](image)

If PMC surfaces are used as ground plane then there is improvement in the magnitude of return loss and its value now comes around 7.3 dB due to positive value of reflection coefficient from the PMC ground plane. It should also be noted that PMC structures does not occur in nature.

![Figure 1.8: Return loss comparisons of PEC, PMC and EBG structures (from [103], © IEEE 2003).](image)
The desired value of return loss is obtained when EBG ground planes are used which simultaneously provides positive reflection and minimize surface waves in its band gap. Hence researchers proved that EBG structures have a potentiality to replace PEC as ground plane in low-profile antennas.

In addition EBG structures also find applications with dipole antennas [151], monopole antennas [80], spiral shapes antennas [152-153], circularly polarized curl antenna [154], loop antennas [155], fractal antennas [156] and inverted F type antennas [157].

Broadband Archimedean spiral antenna with EBG ground plane as a low-profile configuration was reported in [158-159]. Bow-tie antennas and open sleeve antennas for broadband applications are also discussed with EBG structures in [160-161]. Mutual coupling reduction in low profile antenna array [162-163] and curl antenna array is reported in [164].

In slot antennas EBG structures have been used to enhance the radiation characteristics of antennas [165-167]. A triple band slot antenna with EBG feed is discussed in [168]. Applications of EBGs with waveguide slot antenna are discussed in [169].

1.12.3 EBG Structures Applications with High Gain Antennas

In [170-171] applications of EBGs with high gain antenna are discussed. With the applications of EBGs as super states the gain enhancement of antennas are reported in [172-176]. Circularly polarized antenna with improved antenna bandwidth using EBGs are reported in [177]. Applications of EBGs in design of horn antennas are presented in [178-180]. In [181] the applications of EBGs in adaptive antennas and beam steering antennas are discussed. Use of EBGs like rectangular shaped, circular shaped and elliptical shaped are used in directive antenna designs [182] and with reflector antenna are reported in [183].

1.12.4 EBG Structures Applications with Devices used in Real Life

Applications of EBGs in base station antennas and mobile handset antennas are shown in [184]. Antennas integrated with EBG structures used with WLAN and microwave links are studied in [185-186]. EBG antennas for Global Positioning System (GPS) applications are discussed in [187].

EBGs antennas are used with Radio Frequency Identification (RFID) readers [188], wearable devices [189] and biotelemetry systems [190]. Furthermore, EBGs has also been used with direction finding applications [191], radars [192], Unmanned aerial vehicles (UAV) [193], Waveguides [194], microwave circuitries [195] and EM interference reductions [196].
1.13 Literature Review of Notched Antenna Designs

Notch is generated in different antennas by modifications in the radiators. In UWB range many narrow band devices produce interferences and hence these notch antennas have multiplied importance. Different kinds of perturbations can be made in radiators to obtain single, double and triple notches.

![Figure 1.9: Design of the antenna: (a) Upper view, (b) Cross view, (c) Bottom view, (d) Measured and simulated results of VSWR. (Case I: with a U-shaped slot filter, Case II: without a U-shaped slot filter) (From [197], © IEEE 2006).](image-url)
Figure 1.9 (a) top view, Figure 1.9 (b) side view and Figure 1.9 (c) bottom view shows a staircase shape and small volume \((25 \times 26 \times 1 \text{ mm}^3)\) half bowtie shaped antenna [197]. The band rejection filter is made by etching a U-shaped notch in the radiating element, thereby prevents the interference from WLAN Band. Figure 1.9 (d) also shows the measured value with and without the U-shaped slot filter. When the slot from the radiating element was removed, the notched band was also omitted. The WLAN notched bandwidth was measured and it was found to be of 860 MHz from 5 to 5.86 GHz. In [198] the band notches were achieved by adding independent controllable strip to the fork shaped antenna. One antenna was designed for a single notch band and the other is for dual band notch design.

The antennas were fabricated on a \(24 \times 36 \text{ mm}^2\) RO4003TM substrate with a dielectric constant of 3.38 and a substrate thickness of 1.524 mm. The geometry of the UWB antenna with single band-notched characteristic is illustrated in Figure 1.10 (a, b) and Figure 1.10 (c) respectively. The width of the controllable strips has a minor effect on the notch frequencies. Figure 1.10 (d) shows the measured and simulates VSWR with frequency of single band notch antenna and Figure 1.10 (e) shows the relation of same antenna with dual band notches.

In [199] a hook shaped DGS on both sides of ground plane, a \(\Omega\)-shaped slot on the radiating element and a semi octagon ring on the back side of antenna is used to obtain the triple notch antenna. By adjusting the size and location of these slots and rings the notch can be obtained at the desired frequencies. Figure 1.11 (a) shows the top view and Figure 1.11 (b) shows bottom view of geometry and configuration of the presented antenna, which is printed on a substrate with size of \(36 \times 34 \text{ mm}^2\), thickness of 1 mm, and relative permittivity of 2.65.

The measured impedance bandwidth shown in Figure 1.11 (c) defined by VSWR<2, design frequency of 10.1 GHz (2.9–13 GHz), with the triple notched bands of 3.3–3.9 GHz, 5.2–5.35GHz, and 5.8–6.0 GHz are obtained.

In [200] a straight open ended \(\frac{\lambda}{4}\) slot was made for notch in 3.3-3.7 GHz band on the radiating element with three semi-circulars \(\frac{\lambda}{2}\) slots are also made in the patch to generate notch in 5-6 GHz for WLAN band and 7.25-7.75 GHz for downlink X-band satellite communication system. The antenna has a compact volume of \(25 \times 29 \times 0.8 \text{ mm}^3\) and designed on FR-4 substrate with a relative dielectric constant of 4.4 and loss tangent of 0.02.
Figure 1.10: Arrangement of the single band-notch UWB antenna (a) topmost view (b) lowest view (c) Dual band-notch UWB antenna, (d) Simulated and measured VSWR characteristics of the single band-notches, (e) Simulated and measured VSWR characteristics of the double band-notches (From [198], © IEEE 2009).
The antenna design is shown in Figure 1.12 (a) and Figure 1.12 (b). The shape and locations of slots can be determined with the aid of Figure 1.12 (c) and Figure 1.12 (d). The parameters used in these calculations are guided wavelength $\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}}$, where $\lambda_0$ is the free-space wavelength and effective dielectric constant, $\varepsilon_{\text{eff}} = \frac{(\varepsilon_r+1)}{2}$. A straight slot $S_1$ was cut near the left side edge of the radiating patch which is about a quarter of the guided wavelength ($\frac{\lambda_g}{4}$) for WiMAX band.

Figure 1.11: Design of the antenna with notches (a) Upper view, (b) Back view, (c) Tested and simulated VSWR of the UWB notched antenna (From [199], ©IEEE 2009)
To obtain notches at higher frequencies, semi-circular slots $S_2$ (with radius $R_2 = 5$ mm) and coupled slots $S_{3a}$ and $S_{3b}$ (With radius $R_3 = 3.8$ mm) cut in the middle of the radiating patch are used. The length of slot $S_2$, $L_{S2} = \pi \left( R_2 + \frac{0.7}{2} \right) = 16.8$ mm, is about half of the guided wavelength ($\frac{\lambda_g}{2}$) calculated at 5.45 GHz in the WLAN band. The length of slots $S_{3a}$ and $S_{3b}$, $L_{S3} = \pi \left( R_3 + \frac{0.5}{2} \right) = 12.6$ mm, is about half of the guided wavelength ($\frac{\lambda_g}{2}$) calculated at 7.4 GHz in the downlink of X-band satellite communication systems. Figure 1.12 (e) shows the variation of $S_{11}(\text{dB})$ versus frequency with triple notches.

**Figure 1.12:** Design of the antenna (a) Top view, (b) Side view, (c) Slot configuration (d) Effective length of the slots, (e) Tested and simulated return loss of the antenna (From [200], © IEEE 2011)
1.14 Motivation and Goals

Microstrip Antenna suffers from low bandwidth (<5%) and low gain predominantly owing to promulgation of surface waves. Surface wave promulgation is severe problematic in microstrip antenna. Surface wave diminishes antenna efficiency and gain, limits bandwidth, surges end-fire radiations, escalates cross-polarization and limits the useful frequency range of microstrip antennas. Microstrip Patch Antenna (MPA) has a conducting patch of low surface impedance printed on a grounded dielectric substrate. The ground plane supports propagating TM surface waves. These waves travel along the surface that causes undesirable end–fire radiations. The image current is out of phase with antenna current thereby causes fading of the radiation pattern.

Mutual coupling happens together in surface waves (the primary mode TM$_0$ requires zero cut-off frequency and is permanently present but influence is more noticeable in E-plane rather than H-plane) and in expressions of space waves. The elements initiating mutual coupling are substrate dielectric strength, substrate thickness and space among individual patches. Surface waves turn out to be reasonably greater than space waves when high dielectric and high thickness of substrate is used.

In addition in many of the stated applications of MPA there would be a multi-frequency operations requirement. So the improvement of the bandwidth and the attainment of multi frequency setup are major tasks for the MPA.

Considerable research has been done in the use of UWB systems since the Federal communication commission (FCC) unconfined the frequency range 3.1-10.6 GHz. It is because of their small power intake, less budget, accurate locating and encouraging contender for short-range high-speed indoor information transmission. Circular monopoles are a good example for UWB uses owing to their advantages like simplicity of production, satisfactory radiation characteristics and huge impedance bandwidth. Nevertheless, narrowband arrangements also function in this frequency like worldwide interoperability for microwave access WiMAX band (3.3-3.8 GHz), wireless local area network WLAN band (5.15-5.825 GHz) and X-Band downlink satellite communication band (7.1-7.9 GHz). To avoid any intervention from these systems it is required to design UWB antenna with band notch features.

Multiple-input–multiple-output (MIMO)/Diversity antennas based communication systems have multiple antennas that are used at transmitter and receiver terminals to improve the data
rate in multipath signal propagation. The signal strength can be improved by sending data bits with multiple antennas at the transmitter and data bits are reassembled at the receiver. When MIMO systems are used for compact portable devices, high electromagnetic coupling between antennas affect the system performance considerably.

This thesis aims to contribute towards research of Electromagnetic Band Gap (EBG) structures integrated with microstrip antenna. A survey on EBG structures, its properties, bandwidth enhancement due to suppression of surface waves and reduction of mutual coupling with EBG structures is reported. Lastly, development of notched UWB with uniplanar and mushroom EBG structures which is antenna design independent approach has been carried out.

1.15 Organization of the Thesis

This thesis is divided into eight chapters. The first chapter is devoted to introductory overview and literature survey.

Second chapter deals with analysis of Electromagnetic Band Gap Structures (EBG), EBG structures properties, bandwidth enhancement due to suppression of surface waves and reduction of mutual coupling.

Third chapter deals with design and development of notched UWB with mushroom EBG structures. The proposed antennas rejects WiMAX band and WLAN band.

Fourth chapter deals with design and development of notched UWB with uniplanar EBG structures. A significant feature of uniplanar EBG is elimination of perpendicular vias, thus it shortens fabrication process and makes them harmonious with microwave and millimetre circuits. The operation mechanism of uniplanar EBG is similar to mushroom type of EBG and can be explained by LC model.

Fifth chapter employs altered mushroom-type Electromagnetic Band Gap (EBG) structures to accomplish band-notched designs. Approximately 34% decline in dimension of EBG patch is attained if conventional mushroom type EBG is switched to proposed inductance improved altered mushroom shape EBG structure. The proposed WiMAX and WLAN Defected Ground Compact EBG (DG-CEBG) structures illustrate a compactness of around 46% and 50% respectively over conventional mushroom EBG structures.

Sixth chapter deals with antenna that rejects WiMAX band, WLAN band and X-Band downlink satellite communication band (7.1-7.9 GHz). Antennas utilise mushroom-type and uniplanar Electromagnetic Band Gap (EBG) structures to achieve band-notched designs.
Seventh chapter deals with MIMO/Diversity antenna with dual/triple band-notched characteristics. This chapter proposes MIMO/Diversity with dual notch antenna that rejects WiMAX band and WLAN band. In this chapter MIMO/Diversity triple notch antenna with notches in WiMAX band, WLAN band and X-Band downlink satellite communication band (7.1-7.9 GHz) is also proposed. Decoupling strips and slotted ground plane are used to reduce the electromagnetic coupling among two closely spaced UWB monopoles.

Last chapter deals with conclusion and future scope.