CHAPTER 1

Introduction

This chapter starts with a brief overview of the progress in antenna research. Microstrip antennas, Planar inverted F antennas (PIFA), metamaterial antennas are described to portray the recent progress in antennas from half wavelength and quarter wave resonant antenna systems to sub-wavelength ultra miniaturized antennas. The chapter also presents the coplanar waveguide and its potential applications in microwave circuits and antennas. Finally the motivation behind the development of 'coplanar antenna' and the thesis organization are described.
1.1 Introduction

The foundations for wireless communication research and industry were established in 1864, when James Clerk Maxwell predicted that the electric and magnetic fields will allow energy to be transported through materials and space at a finite velocity [1]. Heinrich Rudolf Hertz demonstrated Maxwell’s theory of electromagnetic radiation in 1888 by his classical spark transmitter. Hertz’s apparatus demonstrated the first transmission of regulated radio waves, the ‘new form of energy’ [2].

The great Indian scientist Jagadish Chandra Bose made a revolutionary attempt to demonstrate radio communication. In 1895, Bose gave his first public demonstration of electromagnetic waves. The wavelengths he used ranged from 2.5 cm to 5 mm. He was playing at 60 GHz over one hundred years ago! Bose’s investigations included measurement of refractive index of a variety of substances. He also made dielectric lenses, oscillators, receivers, and his own polarization device.

Guglielmo Marconi, dubbed the father of the wireless communications, took the discoveries of Maxwell and Hertz. It was in 1897 that Marconi demonstrated the practical applications of wireless communication, when he established continuous radio communication between the shore and ships traveling in the English Channel [3]. By mid December in 1901, Marconi took a much greater step by performing the first transcontinental wireless communication, between England and Canada. This achievement triggered the scientists and engineers all over the world towards wireless communication.
1.2 Overview of Antenna Research

Prior to World War II, most antenna elements were of wire types such as long wires, dipoles, helices, rhombuses etc., and were used either as single elements or as arrays. In the year 1926 Yagi-Uda antenna was introduced [4], which received wide popularity due to the simple array structure and excellent radiation performance. It is still being used as home TV antenna.

World War II was the most flourishing period in antenna research. During and after World War II, many other radiators were introduced. Many of these were aperture type such as open ended waveguides, slots, horns, reflectors and lenses. They were employed for radar, remote sensing and deep space applications [5]. In 1950s a breakthrough in antenna evolution was created by V.H Ramsey [6] which extended the maximum bandwidth as great as 40:1 or more. The structure is specified entirely by angles, instead of linear dimensions, they offered an infinite bandwidth and popularly referred to as frequency independent antennas.

It was not until almost 20 years later that a fundamental new radiating element, which has received a lot of attention and many applications since its inception, was introduced. Microstrip antennas received considerable attention starting in the 1970s, although the idea of a microstrip antenna can be traced to 1953 [7]. Microstrip antenna is simple, lightweight, inexpensive, low profile and conformal to Aircraft, Missile etc. Major advances in millimeter wave antennas have been made in recent years,
including integrated antennas where active and passive circuits are combined with the radiating elements into one compact unit to form monolithic circuits [8].

The inherent narrow bandwidth properties of microstrip antennas has limited its usage from many applications. Recently, printed monopole elements have received wide acceptance due to its omni directional radiation characteristics and compact nature. Very recently ultra wideband communication has received wide popularity. It can provide high speed data transfer rate for short range applications. The wide band behavior of ultra short pulse used for this communication requires ultra wide band antennas to accommodate the large frequency spectrum. This is one of the developing areas in antenna design [9]. The time domain characterization of the antenna and formulation of transfer function for such antennas are active research topic in these days.

There has been much interest in electrically small antennas. Antennas that are electrically small, efficient, and have significant bandwidth would fill many needs if antenna engineers could reconcile these usually contradictory requirements. This is especially true recently with increased uses of wireless technologies for communications and sensor networks. It is well known that small electric dipole antenna is an inefficient radiator, i.e., because it has a very small radiation resistance with very large capacitive reactance. Consequently, to obtain a high overall efficiency, considerable effort must be expended on a matching network that produces an impedance that is conjugately matched to the dipole's impedance; i.e., it forces the total reactance to zero by introducing a very large inductive reactance which cancels the very large capacitive reactance of a small electric dipole, and that then matches this resonant system to a feed
network. Recently, this problem has been overcome by introducing metamaterial concept in antennas. A metamaterial medium is introduced in antennas to obtain electrically small antenna element with good efficiency [10].

Antenna research is now progressing rapidly. Active integrated antenna technology allows the integration of active devices with antenna elements, and the radiator is assigned with some other functions in addition to its role as a radiator in communication systems.

1.3 Small mobile terminal antenna performance and effect of ground plane

In designing antennas for small mobile terminals, the prime considerations have been taken into account are

1. small size
2. light weight
3. compact structure
4. low profile
5. robustness
6. flexibility
7. low cost
8. ease of mass fabrication

In addition to these, durability against the users rough handling, environmental conditions, such as temperature variations should be taken into account. From the 1980s to the present the downsizing of mobile terminals made remarkable progress and, accordingly, the size of the antennas are becoming smaller. The miniaturization of mobile handset is beneficial for users. It is a serious challenge for
antenna engineers. The miniaturization should not sacrifice the antenna performance [11].

Almost all of the equipment cases in these days are made of plastics, not of metals. Some ‘conducting materials’ existing in the equipment will also act as a radiator. The typical conducting material in the equipment is a rectangular shielding plate or box, where RF and other circuits are included. Usually a built-in antenna element is placed on this plate or box, and it acts as a ground plane.

As a ground plane performs as a part of a radiator, when a small antenna element is placed on it and induces currents on it, the antenna’s size is effectively enlarged and, hence, the antenna’s performance is enhanced. The gain and bandwidth may be increased, although this depends on the size of the ground plane and the type of the antenna. An important conclusion obtained from the research is that the role of ground planes in mobile communication equipments is very important. The ground plane contributes very much to the total radiation.

1.4 State of the Art technologies

Mobile communications, wireless interconnects, wireless local area networks (WLANs), and cellular phone technologies are the most viable cost effective communication systems enabling user mobility. Naturally, these applications require efficient antennas. The portable antenna technology has grown along with mobile and cellular technologies. It is important to have the proper antenna for a device. The proper antenna will improve transmission and reception, reduce power consumption and finally results a cute compact device with market demands.
Antennas used for early portable wireless handheld devices were the so-called ‘whip’ antennas. The quarter-wavelength whip antenna was very popular, mostly because of its simple structure and omnidirectional radiation pattern [12]. New antenna designs have appeared on radios with lower profile than the whip antenna and without significantly affecting the performance. The commonly used monopole antennas possess a number of drawbacks. Monopole antennas are relatively large in size and protrude from the handset case in an awkward way.

In the past few years, designs based on the Planar Inverted-F Antenna (PIFA) and Microstrip Antennas (MSA) have been popular for handheld wireless devices due to low profile geometry. Conventional PIFAs and MSAs are compact, with dimensions approximately a quarter to a half of the wavelength. These antennas can be further optimized by adding new parameters in the design, such as strategically shaping the conductive plate, or judiciously locating loads or slots etc.

The major limitation of many low-profile antennas is narrow bandwidth. Typical conventional PIFA’s have 5% bandwidth, but advanced designs offer wider bandwidth. A variety of techniques for broadening bandwidth have been reported, including the addition of a parasitic structure whose resonant frequency is near that of the driving antenna structure. One example described in the literature is a stacked microstrip patch antenna [12].

In addition to broadband operation, one has to consider the development of multiband antennas. Dual-band and tri-band wireless phones have become popular recently because they permit people to use the same phone in two or three networks that have different frequencies.

Development and Analysis of a Compact Dual-band Coplanar Antenna
The following sections describe the details of different antenna technologies widely used in advanced wireless communication systems.

1.5 Microstrip Antenna

A class of antennas that has gained considerable popularity in recent years is the microstrip antenna. A typical microstrip element is illustrated in Fig. 1.1

![Fig. 1.1 Geometry of a conventional microstrip antenna excited using a microstrip line](image)

There are different types of microstrip antennas, but their common features are:

1. A very thin flat metallic region often called radiating patch
2. Low loss isotropic and homogenous dielectric substrate of relative dielectric constant $\varepsilon_r$ and thickness 'h'
3. Ground plane, which is usually much larger than the patch
4. Feed, which supplies the RF power to the radiating patch
Microstrip elements are often constructed by etching the radiating patch (and sometimes the feeding circuit) from a single double sided substrate. The length of the patch is typically about a half of the wavelength. A commonly used dielectric for such antennas is Poly Tetra Fluro Ethylene (PTFE), which has a relative dielectric constant of about 2.2. Sometimes a low-density “honeycomb” material is used to support the patch. This material has a relative dielectric constant near unity and usually results in an element with better efficiency and larger bandwidth [13] but at the expense of an increase in element size. Substrate materials with high dielectric constants can also be used. Such substrates result in elements that are electrically small in terms of free-space wavelengths and consequently have relatively small bandwidth and low efficiency.

The microstrip antennas are popular due to the following:

1. Low-profile structure
2. Easy and inexpensive to manufacture in large quantities using modern printed-circuit techniques.
3. When mounted to a rigid surface they are mechanically robust
4. It can be designed to produce variety of patterns and polarizations, depending on the mode excited and shape of the patch.

Active elements can be easily added by a via between the patch and the ground plane. Using such loaded elements, the antenna characteristics can be controlled. These advantages must be weighed against the disadvantages which can be most
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succinctly stated in terms of antenna quality factor, Q. Microstrip antennas are high-Q devices. High-Q elements have small bandwidths. Increasing the thickness of the dielectric substrate will reduce the Q and increase its bandwidth. But thick substrate will excite unwanted surface waves and reduce the efficiency [13].

1.6 The Planar Inverted-F Antenna

The planar inverted F antenna (PIFA) is commonly employed in mobile hand sets [14]. The small size and low profile nature of the PIFA made it an excellent choice on portable equipment. The PIFA typically consists of a rectangular planar element, ground plane, and short circuited plate as shown in Fig. 1.2.

![Fig. 1.2. Planar Inverted F antenna (PIFA) excited using a coaxial transmission line](image)

The PIFA can be thought of as a combination of the inverted-F (IFA) antenna and the short circuited rectangular microstrip antennas (SCMSA), as shown in Fig. 1.2. Both the IFA and SCMSA have smaller bandwidths, but PIFA has sufficient bandwidth to cover popular communication bands (about 8%). The PIFA is an IFA in which the wire radiator element is replaced by a strip to increase the bandwidth.

CREMA, CUSAT
The PIFA also can be viewed as a short-circuit microstrip antenna resonating at the dominant $\text{TM}_{100}$ mode. The length of the rectangular element is halved by placing a short-circuit plate between the radiator element and ground plane. When the width of the short-circuit plate is narrower than that of the planar element, the effective inductance of the antenna element increases, and the resonant frequency becomes lower than that of a conventional short-circuit MSA having the same size. As a result, the size of the short-circuit MSA can be further reduced.

1.7 Metamaterial antennas

Over the last few years, there has been considerable research effort on the analysis and design of metamaterial structures for the microwave and millimeter wave frequency regimes [15, 16, 17]. Metamaterials have been developed and shown to exhibit properties such as electromagnetic band gaps (EBG), artificial magnetic conductor (AMC) behavior and negative refractive index. These properties of metamaterial structures have opened up new directions towards enhancing the performance of microwave components and overcoming current limitations.

Portable devices have become one of the necessary appliances for our daily lives. To conveniently carry these portable devices such as cell phones, media players and laptops, they are designed to be compact and lightweight, without sacrificing performance or functionality. The challenge to implement such small devices is to mount all the necessary circuits onto a small highly integrated transceiver unit. Among all
the components, the antenna is one of the most challenging device to be scaled down in size because the size of the conventional antennas depends on the operation frequency of the required applications, which is usually in the MHz or low GHz range.

The traditional half-wavelength antenna cannot be incorporated in the space limited RF front-end modules. Therefore, many researchers are investigating different methods to realize small antennas such as using high dielectric constant substrate, shorting pin and folded monopole etc. Recently, metamaterial based transmission lines have been developed and have been shown to exhibit unique features of anti-parallel phase and group velocities and zero propagation constant at a certain frequency at the fundamental operating mode These metamaterials have been used to realize novel subwavelength antennas. An interesting design consisting of a dipole with left-handed loading is explained [18]. The antenna is composed of a ladder network of periodic structure of unit cells having series capacitors and shunt inductors. The geometry of the proposed antenna is shown in Fig. 1.3 below.
Placing capacitors into one side of the network leads to out of phase currents with different amplitudes that allow strong radiation. The numerical analysis show that the antenna has a length of 0.15 wavelengths in free space, input impedance close to 50 Ω and well behaved radiation patterns. The input impedance is close to 50 Ω is achieved in a series resonance at 451 MHz. Note that the size of the device is less than 0.25 λ, which is usually needed in any resonant antenna systems. Metamaterial antenna is becoming a promising area of research.

1.8 Coplanar Wave Guides and its applications

The coplanar waveguide (CPW) was proposed by Wen [19] in 1969. A conventional CPW on a dielectric substrate consists of a center strip conductor with semi-infinite ground planes on either side as shown in Fig. 1.4.
This structure supports a quasi-TEM mode of propagation. The CPW offers several advantages over conventional microstrip line. First, it simplifies fabrication, second it facilitates easy shunt as well as series surface mounting of active and passive devices [20] to [21]; third, it eliminates the need for wraparound and via holes [22] and [23], and fourth, it reduces radiation loss [24]. In addition a ground plane exists between any two adjacent lines, hence cross talk effects between adjacent lines are very week [25]. As a result, CPW circuits can be made denser than conventional microstrip circuits. These, as well as several other advantages, make CPW ideally suited for MIC as well as MMIC applications.
1.8.1 Types of Coplanar Waveguides

Coplanar waveguides can be broadly classified as follows:

- Conventional CPW
- Conductor backed CPW
- Micromachined CPW

In a conventional CPW, the ground planes are of semi infinite extent on either side. However, in a practical circuit the ground planes are made of finite extent. The conductor-backed CPW has an additional ground plane at the bottom surface of the substrate. This lower ground plane not only provides mechanical support to the substrate but also acts as a heat sink for circuits with active devices. The micro machined CPWs are of two types, namely, the microshield line [26] and the CPW suspended by a silicon dioxide membrane above a micromachined groove [27].

1.8.2 Field distribution in CPW

The electric and magnetic field distribution in CPW is depicted in Fig. 1.5 below. Usually the CPW is excited by giving signal to the centre strip with respect to the ground strips. This produce a field distribution similar to the Odd mode distribution in coupled slot lines. That is the power is coupled by the out of phase electric field distribution in the two slots and magnetic field encircling each strips. This produce a magnetic wall at the plane passing though the centre of the signal strip as shown in Fig. 1.5.
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The system is excited by connecting centre conductor of a coaxial connector to the signal strip and outer ground conductor to the two ground strips. This forcefully excites the odd mode field distribution in CPWs. In this case the field distributions in the slots are out of phase, and it cancels at the far field. This field distribution is maintained in this structure due to the feed symmetry.

1.8.3 Applications of CPW

The CPW finds application in almost all the fields of microwave engineering. The microwave circuits always prefer to use CPW based designs due to its uniplanar nature. The amplifiers, active combiners, frequency doublers, mixers, and switches has been realized using CPW. The CPW amplifier circuits include millimeter-wave amplifiers [28, 29 and 30] distributed amplifiers [31], cryogenically cooled amplifiers [32], cascade
amplifiers [33], transimpedance amplifiers [34], dual gate HEMT amplifiers [35], and low-noise amplifiers [36].

Another important area of its application is in Microelectromechanical Systems (MEMS) Switches. The rapid progress made in the area of semiconductor wafer processing has led to the successful development of MEMS based microwave circuits. In a CPW the conductors are located on the top surface of a substrate which makes it ideally suited for fabricating metal membrane, capacitive, shunt-type switches [37]. CPW MEMS shunt switches with low insertion loss, reasonable switching voltages, fast switching speed, and excellent linearity have recently been demonstrated. These switches offer the potential to build new generation of low-loss high-linearity microwave circuits for phased array antennas and communication systems.

The CPW is invariably using in antenna designs as the feed of the radiating element and as radiating system. Coplanar Waveguide Patch Antennas are available in literature [38]. The feed system in these antennas is directly coupled, electromagnetically coupled, or aperture coupled to the patch.
1.9 Motivation of the present research

'Acceleration or deceleration of charges creates Electromagnetic radiation' [39]. To create charge acceleration or deceleration there must be a bent, curve, discontinuity or termination. This is the fundamental idea behind any antenna system. Discontinuities in transmission lines excite spurious modes to satisfy the boundary conditions. In a normal closed transmission line, such as wave guide or coax, the spurious modes excited by discontinuities soon die out because they cannot propagate. The electric or magnetic fields in the region of the discontinuity appear as capacitive or inductive reactance to the transmission line.

If the transmission line is open or is opened by a discontinuity (a slot or hole), then the higher-order modes generated can radiate energy. The surface wave transmission lines will radiate at discontinuities. They include dielectric slabs, dielectric rods, and corrugated metal surfaces. At the point of excitation and at the point of termination, the higher-order modes generated will radiate.

It is worth noting that there are many antennas in use that can be viewed as a modification of transmission lines. For example consider a conventional half wave dipole antenna. It consists of two flared arms at the end of a balanced transmission line. The antenna becomes an efficient radiator when the two arms are flared apart. Here, the flaring makes a discontinuity, producing current distribution on the arms, and reinforced at far field to obtain omni directional radiation coverage. The transition of a twin wire balanced transmission line to a dipole is depicted in Fig. 1.8 (a) and (b).
In the case of a horn antenna, one end of the waveguide is transformed to a discontinuity. A field distribution is then formed at the aperture of the horn producing radiation intensity at far field. We can flare either E or H planes or both the planes. Fig. 1.9 shown below clearly shows the transformation of a rectangular waveguide to a pyramidal horn antenna.

The printed antenna technology has gained the attention of mobile wireless system designers due to its attractive features like light weight, ease of fabrication and low cost of production. Microstrip antenna technology is the pioneer of this kind. The microstrip antennas are an extension of the microstrip transmission line. As long as the physical
dimension of the strip and the relative dielectric constant remains unchanged, virtually no radiation will occur. By shaping the microstrip line into a discontinuity, power will radiate off from the abrupt ends in the strip line. The transformation of a simple microstrip line to a microstrip antenna is depicted in Fig. 1.10 below.

![Transition of microstrip line to a rectangular microstrip antenna](image)

This is the fundamental principle behind radiation from a microstrip structure. The above discussion concludes as follows: *any transmission line can be configured as a radiating system by properly modifying its structural parameters, and or feed point.*

There are several papers in literatures regarding the leaky behavior of the CPW [40, 41 and 42]. They conclude that the structural parameters of the device strongly influences the leaky modes excited on the structure. But unfortunately the leaky modes are excited at higher microwave bands. This restricts the use of the leaky phenomenon for compact efficient radiator applications.

But according the transmission line perspective, the discussion above strongly says that the CPW can radiate electromagnetic energy if the feed point and structural parameters are properly optimized. This is the fundamental concept behind this thesis work. Consider the case of a conventional coplanar waveguide transmission line shown in Fig. 1.11
The device carries the electromagnetic energy from one end to other by means of a slot mode. The fringing field distribution at the two slots are due to the air dielectric interface in the slots, as depicted in the above figure. The direction of the distribution is obviously out of phase and thus cancels at the far field. That is device behaves as a pure transmission line and thus the radiation from the structure is negligible. The only way to get radiation from the device is by means of transforming the slot modes in such a way that the fringing fields at the two slots are in phase, forming a reinforced radiation intensity at the far field. This is the key idea behind the present work.

By introducing an offset for the feed point location on the centre strip of a coplanar waveguide structure, a radiating mode is excited at lower microwave bands of
the EM spectrum. The E-field distribution at the slots of the device, for the new mode thus excited will looks like as depicted in Fig. 1.12 below.

Fig. 1.12. Offset fed coplanar waveguide with in phase field distribution in the slots

The two slots are very close in terms of its operating wavelength and thus the radiation pattern of the device will not be suitable for mobile communication application. That is by properly optimizing the spatial distance between the slots and making the in-phase field distribution in the slots a new antenna element can be derived. The new antenna derived from the concept explained above is termed as 'coplanar antenna'. The conductor backed CPW (CBCPW) has not been selected purposefully for the study because the conductor backing will restrict the radiation pattern to a hemisphere.
1.10 Thesis Organization

Chapter 1 describes an overview of antenna research, state of the art technologies in antennas, coplanar waveguide, its applications and the motivation of present research.

Chapter 2 presents review of literature concerning the present work. Antennas for mobile communications, multi-band and broad-band techniques in printed antennas, antenna miniaturization schemes, leaky behavior in coplanar waveguides and different types of coplanar antennas are referred in detail. Finally, overview of the progress in FDTD analysis is referred.

In chapter 3, the antenna fabrication method and substrate materials used are described. The experimental facilities utilized are also described. The measurement methods employed for characterizing the antenna presented in the thesis is also described. Some part of the simulation is done using commercial packages like IE3D and HFSS. The basic characteristics about these packages are also explained in this chapter.

The principle behind the PML based FDTD computational method is described in Chapter 4. The theoretical investigations on offset fed coplanar waveguide resonance, radiation and the coplanar antenna are derived using PML based FDTD method.
Chapter 5 describes the theoretical investigations on the radiation and resonance phenomena in coplanar waveguide structures. Initially a conventional CPW is analyzed using FDTD. Then characteristics of the device are analyzed when the CPW structure is excited using offset feed. The computed field distributions and return loss characteristics are described. The Odd mode and Even mode like excitations schemes are separately studied using FDID. Computed results are compared with the measured values. Finally the parametric analysis is also presented to confirm the resonance phenomenon on coplanar waveguide structure when an offset feed is employed.

The so called 'coplanar antenna' design is studied in Chapter 6. Experimental as well as theoretical observations are compared. Parametric analysis of the antenna and the empirical design equations are also presented.

Chapter 7 describes conclusions of this thesis. The scope for future works are also discussed.

Appendix I and II describes design of two other printed antennas. A compact planar multi-band antenna for GPS/PCS/WLAN applications is presented in Appendix I and a compact active microstrip antenna is presented in Appendix II.
1.11 References


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