This chapter presents different technologies proposed by various scientists and research groups for the development of compact planar Antennas. The main focus is on the development of Coplanar Waveguide Fed antennas in the last few decades. The recent advances in planar antennas are also addressed. The transformation of coplanar waveguides to an efficient radiator is properly investigated and presented in this chapter.
2.1 Introduction

The need of miniaturization in the present day communication industry is challenging. In the present scenario, printed antenna technology is highly suitable for wireless communication due to its low profile and other desirable radiation characteristics. Small monopole type antennas are overruled by compact small antennas for present day mobile communication applications.

Coplanar waveguides (CPW) are printed on one side of a dielectric substrate. CPW have attracted the attention of antenna designers due to their excellent properties like ease of integration with ‘MMIC’, low cost, wide bandwidth, flexibility towards multiband operation, low radiation leakage and less dispersion. The requirement of omnidirectional coverage, light weight and low cost made these CPW fed antennas a good candidate for wireless applications.

The main focus of the thesis is the study of coplanar waveguide transmission line. Rigorous investigations were performed on both the ground plane and signal strip of a coplanar waveguide transmission line to create effective radiation characteristics. Good amount of works have been done to transform CPW line to antenna suitable for mobile phone applications. References on the radiation properties of CPW transmission line have been included in this chapter

2.1.1 Planar Printed antennas

Printed antennas have a variety of attractive properties like compactness, mechanical durability, conformability, and cheap manufacturing costs. They have a range of applications in both the military and commercial sectors, and are often mounted on the exterior of aircraft and spacecraft, as well as in
mobile radio communication devices. Various challenges have to be faced by antenna designers for developing such devices. The chronological development in printed antenna technology is clearly illustrated in the following section.

The basic printed antenna, Microstrip antenna concept was first proposed in 1953 by Dechamps [1] of USA and by Gutton and Baissinot of France [2]. The realization of the microstrip antenna element patented by Munson[3] in 1970 gave a sudden boost to antenna industry.

The basic rectangular and circular microstrip patch antennas were proposed by Howell [4]. Later the transmission line model [5], the cavity model [6] and the spectral-domain method [7] were introduced for the analysis of microstrip antennas. The multiport network model generalizes the cavity model[8]. For very thin substrates the resonant frequency and input impedance have limited accuracy using these methods[9]. Moreover, they have limited capacity to handle problems such as mutual coupling, large arrays, surface wave effects and different substrate configuration.

The finite element approach[10] made possible to calculate the fields interior to the microstrip antenna with solutions closest to the true analytical solutions. The spectral domain full wave approach which uses the exact Green’s function for the mixed dielectric nature of the microstrip antenna was proposed by Deshpande and Bailey[11]. Lot of analysis on patch geometries and feed structures were carried out using this technique.

The analysis of a rectangular patch and circular disc were studied using this method by Chew, Aberle and Bailey[12-14]. Studies on various modified
patch geometries were successfully carried out by lot of researchers all over the world for different applications.

John Q Howel [15] studied various types of microstrip antennas and has given design procedures for both linearly and circularly polarized antennas. Microstrip antennas having circular polarization operation have been studied and reported [16-18]. A circular polarized rectangular microstrip antenna with a single point feed was also designed by Haneishi and Yoshida [19].

The preliminary limitation of microstrip antennas was the narrow bandwidth. This was overcome by modifying the patch geometries and also by using stacked patches as radiators [20]. Integral equation method [21-24], cavity model [25-27], transmission line model [28-29] and modal expansion method [30] are the techniques used to solve basic aperture coupled patch antenna geometries.

Y.J. Sung [31] introduced Defected Ground Structures (DGS) on microstrip patch antenna to suppress the higher order harmonics. W.C Liu [32] designed a dual-polarised single layer slotted patch antenna. Y. Qin [33] achieved broadband using an H-shaped patch coupled to a microstrip feed line via a ring slot in the ground plane. But still the enhancement in bandwidth is a serious issue in microstrip antenna designs.

2.1.2 Coplanar Waveguide (CPW) fed Antennas

The emergence of Coplanar Waveguide (CPW) fed antennas revolutionized the antenna industry in terms of cost, compactness, bandwidth etc. The uniplanar characteristics of CPW structures together with their attractive features like low radiation loss and less dispersion in comparison with a microstrip, little dependence of characteristic impedance on substrate parameters etc made them
The development of the Coplanar Waveguide fed antennas from the beginning to recent years is detailed here.

Coplanar Waveguide (CPW) was invented by CPW (Cheng P. Wen) and is discussed in his manuscript entitled “Coplanar Waveguide: a surface strip transmission line suitable for nonreciprocal gyromagnetic device applications” published in 1969[34]. Practical applications of coplanar waveguide have been experimentally demonstrated by measurements on resonant isolators and differential phase shifters fabricated on low-loss dielectric substrates with high dielectric constants. Calculations have been made for the characteristic impedance, phase velocity, and upper bound of attenuation of a transmission line whose electrodes are all on one side of a dielectric substrate. This discovery enabled the microwave researchers to choose a good end transmission line for MMIC devices and for other compact microwave applications.

In 1970 Cheng P. Wen [35] reported the attenuation characteristics of coplanar waveguides. The Q measurements together with the loss characteristics of coplanar waveguides were presented and found to be in conjunction with microstrip lines of the same width and characteristic impedance.

H Matino[36] proposed the characteristic impedance measurement of coplanar waveguide. This letter presents experimental data, and theoretical equation including correction factors, for an effective relative permittivity concerning characteristic impedance. The next year the dependence of the characteristic impedance of a coplanar waveguide was measured as a function of slot width and substrate thickness by P.A.J.Dupuis and C.K. Campbell [37].
A theoretical method was presented by T. Kitazawa in 1976[38] for the analysis of a coplanar waveguide with thick metal-coating. It was shown that the metal coating thickness of the coplanar waveguide causes an increase in wavelength and a decrease in characteristic impedance. They also noted that the changes are about the same as those of a slot line.

E. Mueller [39] measured the effective relative permittivity of unshielded coplanar waveguides. The dependence of the effective relative permittivity of coplanar waveguides was measured as a function of frequency from 3-12 GHz and is compared with the computed values.

The transmission properties of a coplanar waveguide printed on conductor-backed substrates were analysed by Y.C. Shih and T. Itoh in 1982 [40] using the spectral-domain technique. They concluded that for a fixed substrate thickness, the characteristic impedance and the phase constant may be varied independently by simply adjusting the widths of the centre strip and the slots in the transmission line.

A new concept of exciting slotted antenna arrays was proposed by Aleksandar Nesic in 1982 [41] where both the slots and feeder are etched on the same side of the printed circuit board. A channel is cut perpendicular to the slots, and a coplanar waveguide for exciting the slots is inserted into the channel and the concept is experimentally verified on a model.

Analysis of slow wave phenomena in coplanar waveguide on a semiconductor substrate was proposed by Y. Fukuoka and T. Itoh [42] using mode-matching technique. This waveguide is suitable for monolithic microwave integrated circuits due to their coplanar configuration. After a lot of
study on the slow wave phenomena of coplanar waveguide was carried out by scientists and microwave researchers rigorously.

Anand Gopinath in 1982[43] investigated on the losses in Coplanar Waveguides elaborately. Conductor losses in coplanar waveguides have been calculated using a quasi-static Green’s function approach. The conductor, dielectric and radiation losses are used to compute the quality factor of half wavelength resonators and compared with the measurement results.

A coplanar waveguide fed end-coupled resonator band pass filter was proposed and investigated by Dylan F. Williams in 1983[44]. Band pass filter design rules were developed for easy filter synthesis from “prototype” low-pass designs. Measurements of single section resonator Quality factors were used to predict filter insertion losses and verified with lot of examples.

A simplified method for evaluating the line parameters of a coplanar waveguide was presented by Kohji Koshiji[45] in 1983. The TEM mode of propagation was assumed and Laplace's equation is solved by means of the successive over relaxation method. Parameters such as potential distribution electric field, current distribution over conductor surface, characteristic impedance, dielectric loss and conductor loss are analyzed.

A new analytical expression for the impedance and the permittivity of coplanar waveguides with lower ground plane was presented by G. Ghione and C. Naldi[46] on the same year. These calculated expression shows very good agreement with the upper or lower bounds of the parameters, computed via a spectral-domain variational approach.

David A Rowe in 1983 [47] proposed a numerical method to calculate the impedance and the effective dielectric constant for a CPW with a ground plane
under a thin dielectric as a function of CPW parameters for different substrates. These results can be used to design the shielded coplanar waveguides.

The effect on characteristic impedance and line loss by inner conductor offset in a Coplanar Waveguide was reported by Kohji Koshiji and Eimei Shu in 1984 [48]. This effect can be an appreciable factor in designing highly precise circuits, such as MIC’s using coplanar waveguide, or a coplanar-type standing-wave detector.

The influence of various structural parameters on the characteristics of the Metal-Insulator-Semiconductor Coplanar waveguide structure was investigated, together with the effect of the addition of a back conducting plane by Roberto Sorrentino in 1984 [49]. They have developed the design criteria for low attenuation slow wave propagation.

Victor Fouad Hanna and Dominique Thebault [50] investigated theoretically and experimentally, the characteristic impedance and effective dielectric constant of an Asymmetric Coplanar Waveguide with infinite or finite dielectric thickness. It was observed that the line asymmetry decreases the characteristic impedance and increases its relative effective dielectric constant.

D. Bhattacharya in 1985 [51] proposed a simplified formula for the characteristic impedance of coplanar waveguide by determining the static capacitances between the parallel strips and is valid even up to zero gap width. On the same year C. Seguinot [52] suggested a time domain response of MIS Coplanar Waveguides for MMIC’s.

The coplanar waveguides transmission line is compared with a microstrip line in terms of conductor loss, dispersion and radiation into parasitic modes. Robert W. Jackson [53] shows that for high frequency application CPW can be
chosen to give better results in terms of conductor loss and dispersion than microstrip.

K. Koshiji and E Shu [54] developed circulators using coplanar waveguides. One of the circulators designed in this way shows a maximum isolation of 19.1dB, insertion loss 0.8dB and VSWR 1.3 or less at a center frequency 9.56GHz.

D Mirshekar Syahkal in 1986[55] developed a full wave solution to investigate the dispersion in shielded coupled coplanar waveguides. The characteristics of even and odd modes of coplanar waveguide on semi-insulating GaAs substrate were investigated by R. Majidi Ahy in 1987[56]. The guide wavelength for each mode is directly obtained from standing wave measurements by electro-optic sampling, and compared to the theoretical values.

Parasitic effects occurring in actual realizations of coplanar waveguides (CPW) for microwave integrated circuits on GaAs substrates, such as the influence of an upper shield, conductor backing, finite-extent ground planes, and line-to-line coupling, were discussed and evaluated by Giovanni Ghione[57] in 1987.

Robert W. Jackson investigated the electromagnetic coupling possibility of Coplanar Waveguide in 1987 [58]. He proposed a transition which couples coplanar waveguide on one substrate surface (a motherboard) to coplanar waveguide on another substrate surface (a semiconductor chip) placed above the first without using any wire bonds. They also performed full wave analysis using coupled line theory.
A three-port magnetically-tunable ferrite resonator circuit which uses a ferrite resonator and coplanar waveguide on a dielectric substrate was proposed by Koichi Ohwi [59]. M. Riaziat [60] and co-workers investigated the single-mode operation of coplanar waveguides. A grounded coplanar waveguide structure with finite-size ground planes is analysed as three coupled microstrip lines. The three normal propagation modes of this structure are examined for various geometries, and some physical layout guidelines are established.

A lumped equivalent circuit models for several coplanar waveguide discontinuities such as an open circuit, a series gap in the center conductor, and a symmetric step in the center conductor were investigated by Rainee N. Simons [61]. The element values are given as a function of the physical dimensions of the discontinuity. The model element values are de-embedded from measured S parameters. In addition, the effects of the center conductor width and the substrate thickness on the equivalent circuit element values are presented. The characteristics of a CPW right angle bend employing a novel compensation technique are also presented.

A coplanar waveguide array antenna which consists of a coplanar waveguide and wire loop antennas was proposed by K. Nakaoka [62]. The reported antenna has the advantages of wide bandwidth, lower losses in the transmission line and is independent of the thickness of copper clad dielectric.

Full-wave analysis of coplanar waveguide (CPW) and a slotline by the time-domain finite-difference method (TD-FD) was presented by Guo-Chun liang[63] in 1989. The transient propagating waveforms along the coplanar waveguide and slotline, which are excited by retarded Gaussian pulses, are found in the time domain. After the time-domain field distributions are obtained, frequency-domain
parameters such as the effective dielectric constant and the complex characteristic impedance are calculated using Fourier transformations.

John J. Burke [64] described a structure which forms a transition from coplanar waveguide on one substrate to microstrip on another. Energy is transferred via electromagnetic coupling rather than with wire bonds. A full-wave formulation along with the theory of asymmetrically coupled lines is used to analyze the two model transitions.

Robert W. Jackson [65] investigated the mode conversion at discontinuities in finite width conductor-backed coplanar waveguide. The moment method technique is used for CPW gap and shorted end studies. These studies are performed via a fully electromagnetic application of moment method technique and a significant conversion is found to occur at the gap end.

Majid Riaziat in 1990[66] investigated on the propagation modes and dispersion characteristics of coplanar waveguides. Radiation and guided modes are studied on the five subdivided class based on substrate thickness, backside metallization and ground plane width and their effect on loss and dispersion are also described.

Full-wave analysis of shielded coplanar waveguide short-end using transverse resonant method was presented by G.Bartolucci [67]. The resonant frequencies of the structure are computed by the full-wave electromagnetic field analysis. G.C Dalman[68] proposed a waveguide to coplanar waveguide adaptor with low transmission loss and high return loss free from strong resonances over a broadband width.

A method to couple microwave power from a coplanar waveguide to a microstrip line on opposite sides of a ground plane was demonstrated by R.N
Simons and R. Q Lee [69]. The coupler uses a metallic post which passes through an aperture on the ground plane connecting the strip conductor of the coplanar waveguide to the microstrip line.

Mohsen Naghed and Ingo Wolff [70] calculated the equivalent capacitances of coplanar waveguide discontinuities on multilayered substrates using a three-dimensional finite difference method. The application of the method was demonstrated for open ends and gaps in microstrip and coplanar waveguides as well as for more complicated structures such as interdigital capacitors.

An integral equation technique solved by the moment method associated with the single one-port model to analyze radiating end effects of coplanar waveguides (CPW's) was used by M'hamed Drissi [71]. They used series-gap-coupled straight CPW resonators to compare the theoretical results with the experimental ones.

A full-wave analysis of shielded coplanar waveguide two-port discontinuities based on the solution of an appropriate surface integral equation in the space domain was presented by Nihad I. Dib [72]. Equivalent circuit models and closed-form expressions to compute the circuit element values for these discontinuities are also presented.

Teek-Kyung Lee and group [73] characterized the quasi-static capacitance and inductance of the CPW using the Boundary Element Method (BEM). Mikio Tsuji [74] investigated the leakage behavior of coplanar wave guides of finite and infinite widths. They showed that above a critical frequency the dominant mode on coplanar waveguide leaks power in the form of a surface wave on the surrounding substrate, and that this leakage can cause undesirable cross talk and can produce unexpected package effects. Further studies then
revealed several new interesting behavioral features, such as unexpected sharp and deep minima (cancellation effects), various dimensional dependences, and the leakage behavior when the guide width changes from finite to infinite.

R.N Simons [75] demonstrated coplanar waveguide (CPW)/aperture coupled microstrip patch antennas constructed with ground coplanar waveguide (GCPW), finite coplanar waveguide (FCPW) and channelized coplanar waveguide (CCPW). The CCPW/Aperture coupled microstrip patch antenna has the largest bandwidth, whereas the GCPW/aperture coupled microstrip patch antenna has the best front-to-back ratio.

Aperture coupling was successfully employed with Coplanar Waveguide as the feed by Richard Q. Lee in 1992[76]. A grounded CPW with a series gap in the center strip conductor is used to couple microwave power to a microstrip patch antenna through an aperture in the common ground plane. This design permits the insertion of solid state devices in the series gap of the CPW feed and thus, is suitable for use in active antenna or quasi-optical combiner/mixer designs.

Jeng-Yi Ke[77] utilized the spectral domain approach to discuss the dispersion and leakage phenomenon in a coplanar waveguide structure caused by the substrate surface wave. The effective dielectric constant and the attenuation constant due to surface wave leakage are presented and discussed in detail.

Further the researchers elaborately used the coplanar waveguide as a feeding structure for patch antennas. R.L Smith [78] used a coplanar waveguide loop to feed a microstrip patch and E.T. Richardo[79] fabricated CPW on a
single layer substrate with various thickness and used to electromagnetically couple with planar antennas.

The CPW was conformally mapped by M.S. Islam [80] into a parallel plate configuration, where conductor loss is evaluated using a conductor surface impedance which is scaled by the conformal map.

Ming Yu [81] described a new quasi-static technique for the analysis of coplanar and microstrip transmission line discontinuities. The method is a variation of the Space-Spectral Domain Approach (SSDA) which represents a novel combination of the 1-D Method of Line (MOL) and the 1-D Spectral Domain Approach (SDA).

A novel coplanar waveguide fed coplanar strip dipole antenna was presented by K. Tilley [82]. They used a wideband balun to match the antenna. R.R.Kumar[83] reported the dispersion characteristics of conductor backed coplanar waveguide (CBCPW) in a metal enclosure. The higher order modes are also explained by means of an efficient numerical technique, namely the method of lines (MOL). Knowledge of higher order modes is essential for estimating ‘singlemode’ bandwidth and for characterising discontinuities.

A monopole strip antenna which consists of an open ended strip and a three-section coplanar waveguide feed is proposed and its attractive features are described by C. Isik[84] in 1995. He experimentally confirmed the dependence of the antenna on the width and length of the strip.

H.S. Tsai [85] developed CPW-fed multiple slot antennas for active arrays and integrated antennas. This also describes how the antenna can be engineered for a 50 ohm input impedance for a various substrate parameters,
and the concepts are verified using a three-slot antenna on $\varepsilon_r = 2.2$ substrate and a five slot antenna on $\varepsilon_r = 9.8$ substrate.

CPW fed slot antennas printed on multilayer dielectric substrates are numerically analyzed by Jean-Marc Laheurte [86] using a full-wave integral equation technique and the method of moments. The mutual coupling between slot antennas in an array environment is calculated for a three-layer high-low-high permittivity combination.

CPW-fed folded-slot antennas were analyzed using the finite-difference time-domain (FDTD) method by Huan Shang Tsai [87] et.al in 1996. The paper describes the problems encountered in the analysis, compares the theoretical results and measured data, and provides some design information for folded slots. In addition, the paper explores the manipulation of input impedance through the use of additional slots, yielding antennas with broadband $50\,\Omega$ input impedance.

S. Matsuzawa and K. Ito [88] proposed a new structure of circularly polarised printed antenna fed by coplanar waveguide (CPW). FDTD analysis is performed and predicts the radiation of the circularly polarized wave from the antenna.

A microstrip antenna fed by a conductor backed coplanar waveguide was demonstrated by L. Giauffret and J.M. Laheurte in the same year [89]. The addition of a back-side metallic ground plane involves a possible power leakage owing to the excitation of parallel plate modes (PPMs). It is shown that the power leakage can be avoided by a proper choice of substrate characteristics.

The use of an elevated coplanar waveguide (CPW) to increase the bandwidth forced the researchers to theoretically analyze their performance. A full-wave analysis between 10 and 500 GHz of such an elevated CPW using 2-
D FDTD method is presented by S. Hofscnen [90]. The influence of the elevation heights on the capacitance and the loss behavior of the transmission line are discussed in detail.

A circularly polarized patch antenna, fed by a coplanar waveguide was discussed by Y. Turki [91]. The antenna is excited by a couple of 100Ω slotlines which are combined to obtain a 50Ω coplanar waveguide. The axial ratio and the bandwidth of the antenna are similar to those obtained with other types of feeding.

I Linardou [92] described a twin Vivaldi antennas directly fed by coplanar waveguides. All the designs show a centred zero in the E plane with a low cross-polarisation. In the H plane they provide zeros for $\varphi = 90^{\circ}$ and $270^{\circ}$ and are nondirectional for other values.

Erli Chen [93] expressed the analytical formulas using conformal mapping to explain the characteristics of coplanar transmission lines on multilayer substrates. Laurent Giauffret [94] investigated various shapes of excitation slots, such as open stubs, slot loops, and capacitively and inductively coupled slots in terms of return loss and front to back radiated power ratio on CPW fed aperture coupled microstrip antennas.

X.Din and A.F. Jacob[95] presented a new wide slot antenna with capacitively coupled CPW-feed and metallic strips in the apertures. A simplified formula to calculate the input impedance is also proposed by them.

A nonleaky conductor-backed coplanar waveguide (NL-CBCPW) was presented by D.R.Jahagirdar [96] for exciting microstrip patch antennas with emphasis on avoiding the leakage of power and allows easier integration with MMIC’s.
A CPW-fed CPS dipole antenna was presented by AT. Kolsrud, Ming-Yi Li and Kai Chang [97] which operates at dual frequencies with a wideband CPW-to-CPS balun. Dual-frequency operation of the CPS dipole antenna was realised by introducing a small gap in the length of the dipole.

A coplanar waveguide (CPW) fed rectangular patch antenna excited by a rectangular slot-loop was designed for use in the 2.4GHz ISM band by Shih-Wen Lu in 1999 [98]. The size of the slot-loop was chosen to be as close to that of the patch, and the substrate cut is as narrow as possible.

W.S.T. Rowe and R.B. Waterhouse [99] presented a broadband CPW fed stacked patch antenna well suited for integration with monolithic and optical integrated circuits with a bandwidth of 40% on a high dielectric constant substrate.

A new concept for exciting slots with a CPW line based on inductive coupling was introduced by Santiago Sierra-Garcia [100]. He described how this coupling structure can be designed to tune the impedance of the antenna over a wide range. This new coupling topology was particularly suitable for series-fed array configurations and broad-band design.

Masashi Hotta, Yongxi Qian, and Tatsuo Itoh [101] analyzed the leakage loss of the conductor-backed coplanar waveguide (CBCPW) by using a novel hybrid two-dimensional finite difference time-domain/Marquardt curve-fitting technique. The validity and high accuracy of the method was confirmed by comparison with other experimental and theoretical results.

A novel coplanar waveguide fed quasi-Yagi antenna was proposed by J.Sor [102]. A wide bandwidth is achieved by using a broadband coplanar waveguide to a slotline balun. An X-band prototype has been realised which
demonstrates a broad bandwidth (30%), -19dB front to back ratio, and cross polarisation better than -17dB at 10GHz.

A.U Bhobe [103] presented a coplanar waveguide fed slot antenna for wideband operation. This antenna has an impedance bandwidth (for a VSWR < 2) of 49% and a radiation bandwidth of 42% at 4.8GHz, compared to the 12-20% impedance bandwidth of the standard CPW fed slot antenna.

The odd mode of a conductor backed CPW is successfully filtered by introducing a via-hole in one of the lateral ground plane by A. Mebarki[104]. The even mode propagates without being disturbed by the introduction of via hole.

Circularly polarized microstrip antenna with a coplanar waveguide feed was presented by Chih-Yu Huang[105] in 2000. This CP was achieved by insetting a slit to the boundary of the square microstrip patch, which makes possible the splitting of the dominant resonant mode into two near-degenerate orthogonal modes for CP radiation and introducing an inclined slot in the CPW feed line for coupling the electromagnetic (EM) energy to the square patch.

C.H.Cheng[106] proposed a broadband patch antenna fed by a coplanar waveguide based on stacked patch technique for aperture coupled patch antennas. Similarly M.S. Al Salameh[107] proposed a novel coupling scheme to rectangular dielectric resonator antennas. They used narrow coupling slot at the end of a coplanar waveguide (CPW) to couple the energy to a resonator.

Homg Dean Chen [108] proposed a novel compact dual-frequency monopole antenna by introducing an extended conductor line to a rectangular meander monopole. This antenna can operate in the 900 and 1800 MHz bands and provide sufficient bandwidths for the GSM and DCS systems.
Xian-Chang Lin and Ling Teng Wang [109] used photonic band gap structures with cross-shaped or square-shaped lattices on a broadband CPW fed loop slot antenna to achieve harmonic control. The compact PBG structures not only successfully get rid of the higher order modes but also facilitate the impedance matching of the antennas, leading to significant bandwidth augmentation.

A new design of a broadband circularly polarized square slot antenna fed by a single coplanar waveguide (CPW) is proposed by Jia Yi Sze [110] and verified experimentally. Broadband circular polarization (CP) operation is achieved by protruding a T-shaped metallic strip from the ground plane towards the slot center and feeding the square slot antenna using a 50- CPW with a protruded signal strip at 90 to the T-shaped strip.

Design of a coplanar waveguide (CPW) feed square microstrip antenna with circular polarisation (CP) radiation is described by Chih Yu Huang [111]. The CP is achieved by using an asymmetric inductively coupling slot in the ground plane of the CPW feed line.

Horng Dean Chen [112] presented a CPW fed square slot antenna with widened tuning stub to achieve broadband operation. They experimentally showed that the impedance matching for the proposed antenna strongly depends on the location of the tuning stub in the square slot, and the impedance bandwidth is mainly determined by the width and length of the tuning stub.

A coplanar waveguide fed square slot antenna loaded with conducting strips was proposed and experimentally studied to provide broadband design by Jyh Ying Chiou [113]. By choosing a suitable length ratio (ratio of signal strip
in the slot to the loading metallic strip) the impedance bandwidth of the proposed antenna can be significantly increased.

G. Tzeremes[114] presented a quasi TEM equivalent circuit model for two optically driven coplanar waveguide (CPW)-fed slot antennas. This model takes into account both the electromagnetic fields in the CPW structure as well as the effects of the discontinuities of the antenna design.

CPW fed dual band antenna was demonstrated by W.C. Liu[115] in 2004 by inserting a meandering slit at the edge of a rectangular patch. The structure has uniplanar geometry and its compactness makes it suitable for portable mobile communication applications. A rectangular notch is introduced to obtain a broadband dualfrequency operation of a planar monopole antenna fed by a coplanar waveguide (CPW) by W.C. Liu and C.M.Wu[116]

A broadband dual-frequency planar monopole antenna with a coplanar waveguide meandered feed line was introduced by W.C. Liu [117]. This modified feeding technology offers good impedance match for a wide dual-band covering 2.4/5.2 GHz WLAN operations. S.Y.Chen and P.Hsu[118] presented a coplanar waveguide fed capacitive folded-slot antenna for the radio frequency identification application at 5.8GHz.

A rectangular slot antenna with U-shaped tuning stub was proposed by R.Chair[119]. The antenna is excited by a 50Ω CPW to achieve ultra wide bandwidth. A CPW-fed planar ultra-wideband antenna with hexagonal radiating elements is presented by Y Kim [120] in 2004. The frequency band notch characteristic is attained very close to the desired frequency by inserting a V-shaped thin slot on the hexagonal radiating element.
The design procedure of a wideband CPW fed hybrid slot antennas and CPW fed log-periodic slot antennas was presented by Alpesh U. Bhobe[121]. They have studied the impedance matching and the radiation characteristics of these structures using method of moments.

K. Chung, T. Yun and J. Choi [122] presented a CPW fed monopole antenna with parasitic elements and slots to attain wideband characteristics. They introduced the parasitic elements and three slots to increase the impedance bandwidth.

Sierpinski fractal monopole antenna with a CPW feed was presented by M. Kitlinski and R. Kieda[123] for multiband applications. Fourth iteration of the Sierpinski gasket with scale factor δ=1.5 is used as the radiating element. A novel broadband, dual-polarised coplanar-waveguide-fed T-shaped uniplanar antenna was presented by R.B. Hwang [124]. Full wave numerical analysis with experimental results are presented in detail.

J. Yeo, Y. Lee and R. Mittra [125] presented a planar volcano-smoke slot antenna (PVSA) useful for wideband wireless communication applications. The antenna is a planar slot – with an appearance reminiscent of a volcanic crater and a puff of smoke – and is fed by a coplanar waveguide (CPW) to achieve the wide bandwidth. A coax-to-CPW transition, which is crucial for achieving wide bandwidth performance, is also modelled and introduced into the antenna.

A patch monopole antenna for radio frequency identification (RFID) applications using a coplanar waveguide feed with folded slots to expand the impedance bandwidth was presented by W.C. Liu and Z.K Hu[126]. By properly selecting a folded slot on a rectangular patch, compact antenna size, broad impedance bandwidth and good radiation characteristics suitable for the RFID application at 5.8 GHz could be achieved.
A CPW fed right-angled dual tapered notch antenna for ultrawideband (UWB) communication was demonstrated by Y. Kim [127]. The antenna has two tapered notches, which are located at a right-angled corner of a dielectric substrate. The combination of two proposed antennas can be used to eliminate the null areas in the wide-angle direction of the devices.

Shih Yuan Chen [128] presented a broad band radial slot antenna fed by a coplanar waveguide for dual frequency operation. Various frequency ratios for the two operating frequencies can be obtained by varying the included angle between the radial slots and/or by varying the length of the central slot pair. Radiation patterns are broadside and bidirectional.

A new type of CPW-fed dual-annular-slot antenna operating at 5.8 GHz band was introduced by S.-H. Hsu and K. Chang [129]. The authors studied the inductive and capacitive configurations separately and verified the results with measurement.

X.C. Lin and C.C Yu [130] investigated a CPW-fed hybrid antenna consisting of a CPW fed inductive slot and a dual inverted-F monopole antenna. This hybrid antenna exhibits dual-band behaviour with sufficient bandwidths to meet the system requirements of Wireless Local Area Network (WLAN), IEEE 802.11a (5725–5825 MHz), HIPERLAN/2 (5470–5725 MHz) and IEEE 802.11 b/g (2400–2483 MHz).

A coplanar waveguide fed monopole antenna with a planar patch element embedded with a cross slot was presented by C.M. Wu [131] which was capable of generating two separate resonant modes with good impedance match. The authors discussed the design considerations for achieving dual-band operation of the proposed antenna.
A slotted bow-tie antenna with pattern reconfigurability was proposed by Sung-Jung Wu [132] which consists of a coplanar waveguide (CPW) input, a pair of reconfigurable CPW-to-slotline transitions, a pair of Vivaldi-shaped radiating tapered slots, and four PIN diodes. With suitable arrangement of the bias network, the proposed antenna demonstrates reconfigurable radiation patterns in the frequency range from 3.5 to 6.5 GHz.

A low-profile, planar, circularly polarised monopole antenna with a shorting sleeve strip using a coplanar-waveguide transmission line for wireless communication in digital communication system and the global positioning system bands was studied by C.J. Wang [133]. The coupling effect between the monopole antenna and sleeve is utilized properly to excite the two resonant modes.

M.E. Chen [134] presented a CPW fed Ultra Wide Band antenna with an open annulus strip as a ground plane and an open crescent patch in the inner space of the annulus as a radiating element. The radius of the inner crescent patch and the inner radius of the outer annulus should be adjusted carefully to obtain optimal impedance bandwidth.

A uniplanar aperture-coupled slot dipole antenna capable of tri-band operation was presented by Shih-Yuan Chen [135]. By varying the length of the protruded slots the three resonances can be tuned and adjusted. A dipole like radiation pattern with low cross polarized radiation is obtained in all the three bands.

Cheng-Chieh Yu [136] presented a wideband single chip inductor loaded CPW fed inductive slot antenna. An inductor with optimum value is shunt at one
end of the inductive slot antenna to excite additional lower resonance. Moreover, the bandwidth is further widened by enlarging the over the slot ground height.

A coplanar waveguide-fed inductively coupled stepped impedance slot antenna was proposed by Wen-Hua Tu[137] which have a size reduction of 32% compared to a conventional uniform slot antenna.

An UWB printed slot antenna, suitable for integration with the printed circuit board (PCB) of a wireless universal serial-bus (WUSB) dongle was presented by D.D. Krishna [138]. In addition to compact size, the antenna was insensitive to ground plane length variations, making it suitable for WUSB dongle and mobile UWB applications.

P.C. Bybi[139] presented a compact, planar, wideband antenna designed by modifying the coplanar waveguide with a wideband performance. Wide bandwidth >75% centered at 2.50 GHz, quasi omnidirectional radiation coverage, moderate gain and efficiency are the salient features of the antenna.

A dual-band coplanar waveguide (CPW)-fed hybrid antenna consisting of a 5.4 GHz high-band CPW-fed inductive slot antenna and a 2.4 GHz low-band bifurcated F-shaped monopole antenna was proposed and investigated experimentally by Xiang-Chang Lin and Cheng-Chieh Yu [140]. A coplanar-waveguide (CPW)-fed circularly polarized slot antenna with a bandwidth of 31.2% was proposed by Chien-Jen Wang [141].

A triple-band coplanar waveguide (CPW) fed LI-shaped monopole antenna was proposed by Y. Jee and Y.M. Seo[142]. The antenna is composed of an I shaped monopole and a meandered L shaped. These can be independently optimized for particular operating frequency.
D.-O. Kim and C.-Y. Kim [143] proposed the design strategy for the triple-band notched ultra-wideband (UWB) antenna emphasising the rejection characteristic at 3.5/5.5/8.2 GHz bands. They embedded the notching elements onto the primitive antenna to serve as respective stop band filters.

A coplanar waveguide (CPW) antenna was proposed for dual-band WLAN applications by K.G.Thomas and M. Sreenivasan[144]. The antenna comprises of a rectangular patch and rectangular notch, both together providing impedance matching for the lower and upper resonance.

Y.S.Li[145] presented a coplanar-waveguide (CPW)-fed ultra-wideband antenna with dual band-notch characteristics. By cutting two U-shaped slots in the radiation patch and an H-shaped slot in the CPW ground, two band-notched frequencies will appear which reduce the potential interference between UWB systems and narrow band systems.

An endfire directional tapered slot antenna with ultra-wideband characteristic using CPW to wideslot transition was presented by H. Kim [146]. By widening the slot width in the transition, ultra wideband characteristic with enhanced directivity is obtained.

K.P Ray and S.Tiwari [147] presented a coplanar waveguide fed printed hexagonal monopole antenna with ultra wideband application. A parametric study of hexagonal configurations with two different feed arrangements (vertices and side feed) has been carried out to study the effect of feed gap on bandwidth.

Taehee Jang [148] presented the design and analysis of compact coplanar waveguide(CPW)-fed zeroth-order resonant(ZOR) antennas. The CPW geometry provides reduction in antenna size since vias are not required and will provide more design freedom.
2.2 Antenna Fabrication and Experimental analysis

The antenna for a particular application must be fabricated and tested. The various steps employed in the fabrication of a coplanar waveguide fed antenna are listed below.

2.2.1 Selection of a dielectric substrate material

The first important procedure for an antenna designer is to select a suitable dielectric substrate. The electrical and material properties of the selected substrate should match with the required application. The stability of substrate material parameters like dielectric constant and loss tangent with temperature and frequency are important. Since the antenna is coplanar waveguide fed which is uniplanar in nature, single sided substrates are chosen for fabrication.

High performance microwave materials for substrates and packaging industry are in great demand for microelectronic industry. Such materials should possess important properties like low dielectric constant and low dielectric loss to reduce the propagation delay and to increase the signal speed. High Dielectric constant substrates causes surface wave excitation and low bandwidth performance. High loss tangent substrate adversely affects the efficiency of the antenna especially at high frequencies. In addition the material should have high thermal conductivity for dissipating heat. The other important substrate characteristics include the thickness, homogeneity, isotropicity and physical strength of the substrate [149-153]. Increasing the thickness of the substrate will increase the bandwidth at the expense of efficiency owing to the generation of surface waves. There is no ideal substrate; the choice depends on the application of the fabricating device.
Dielectric constant, loss tangent and thickness of the material are important factors to be considered for fabrication. The relative permittivity and loss tangent of a substrate can be measured using various methods [154-155]. In the present study the dielectric constant of the material is measured using Cavity perturbation method. This technique is highly suitable for low loss and low or medium dielectric constant. By using very thin substrates (small volume), it is possible to measure high dielectric constant materials also.

A rectangular waveguide operating in the S or X-band with a slot at the top is used for the measurement. The waveguide is transformed into a cavity by placing two irises at the beginning of the waveguides. Depending on the dimension of the cavity, various modes will develop inside the cavity with various Q and loss. Initially the frequency, bandwidth and quality factor of different modes are measured for the empty cavity. Depending on the type of the cavity more than five modes can be obtained in a particular waveguide. The sample whose properties to be measured should be extremely small. This sample is inserted into the waveguide cavity through the slots created at the top. The sample should be placed in such a way to perturb the field to a maximum level. After inserting the material the shift in frequency, bandwidth and quality factor are again measured. The complex dielectric constant can be calculated using the following equation,

\[
\varepsilon_r = \frac{V_c (f_c - f_s)}{2V_s f_s} + 1
\]

\[
\varepsilon_r' = \frac{(V_c) (Q_c - Q_s)}{4V_s Q_s}
\]

\[
\tan \delta = \frac{\varepsilon_r'}{\varepsilon_r}
\]
Where \( f_c \) = Resonant frequency of the empty cavity
\[ f_s = \text{Resonant frequency of the cavity with sample} \]
\[ V_c = \text{Volume of the cavity} \]
\[ V_s = \text{Volume of the sample} \]
\[ Q_c = \text{Quality factor of the empty cavity} \]
\[ Q_s = \text{Quality factor of the cavity with sample} \]

Thus the dielectric constant of the selected substrate is measured. Next step is to etch the required pattern on this substrate.

### 2.2.2 Photo Lithography

Photolithography or Optical lithography is the process of transferring geometric shapes from a photo-mask to the surface of a substrate. The design of the optimized antenna should be printed on the selected single side substrate. The geometry is drawn using any of the CAD software with high precision. This is printed on a butter paper or transparent OHP sheet. Here a negative photo resist is used for photolithography; therefore an inverse of the pattern is used for making the mask. The substrate with copper on one side is rubbed with metal cloth to remove any of the imperfection and cleaned with acetone to remove impurities on the metal surface. Any disparity in the etched structure will shift the resonant frequency from the predicted values, especially when the operating frequency is very high. A thin layer of photo resist mixed with thinner with 1:2 ratio is coated on the surface of the substrate and dried. Then the mask is placed above the photo resist and is exposed to UV light for a specific time. During this time the UV light is exposed to the portions were the material is required and the photo resist become hard. Then the developer solution removes the resist from unexposed portions. Then the
substrate is applied with suitable dye to have clear visibility for the developed structure. Then it is washed in the running water. The unwanted metallic structure can be removed by etching it in ferric chloride. FeCl₃ dissolves the copper parts except underneath the hardened photo resist layer. The laminate is then cleaned carefully to remove the hardened photo resist using acetone solution. Different steps involved in the fabrication procedure are shown in the figure 2.1.

2.2.3 Antenna Measurement Facilities

Antenna characteristics such as reflection and radiation characteristics are measured using HP8510C vector Network Analyzer, PNAE8362B analyzer and allied setup. The indigenously developed CREMA SOFT is used for the automation and synchronization of all the measurements. In this section a brief description of the basic facilities used for the antenna measurements are presented,
2.2.3.1 HP8510C Vector Network Analyzer

The 8510C series microwave vector network analyzers provide a complete solution for characterizing the linear behavior of either active or passive networks over the 45 MHz to 50 GHz frequency range. The 8510C network analyzer measures the magnitude, phase, and group delay of two-port networks to characterize their linear behavior. Optionally, the network analyzer is also capable of displaying a network’s time domain response to an impulse or a step waveform by computing the inverse Fourier transform of the frequency domain response [156].

![Figure 2.2 Vector Network Analyser based measurement system](image-url)
32bit microcontroller MC68000 based system can measure two port network parameters such as $S_{11}$, $S_{12}$, $S_{22}$, $S_{21}$ and it’s built in signal processor analyses the transmit and receive data and displays the results in many plot formats. The NWA consists of source, S parameter test set, signal processor and display unit. The schematic of the Vector Network Analyzer based measurement set up is shown in figure 2.2.

The synthesized sweep generator HP 83651B uses an open loop YIG tuned oscillator to generate the RF stimulus. It can synthesize frequencies from 10 MHz to 50 GHz. The frequencies can be set in step mode or ramp mode depending on the required measurement accuracy.

The antenna under test (AUT) is connected to one of the port of the S-parameter test set (HP8514B) and the forward and reflected power at the measurement points are separated and down converted to 20MHz using frequency down converter. It is again down converted to 20KHz and processed in the HP8510C processing unit. All the systems discussed above are interconnected using HPIB bus. A computer interfaced to the system is used for coordinating the whole operation remotely. An indigenously developed software CREMA SOFT is used to retrieve and store the measurement data. The data stored is saved in .csv format and can be easily plotted and interpreted using commercially available software’s.

### 2.2.3.2 E8362B Performance Network Analyzer (PNA)

The Agilent E8362B PNA (Performance Network Analyzer) provides excellent performance, advanced automation features, flexible connectivity and is easy to use. Designers and engineers prefer the Agilent E8362B for fast sweep speed, wide dynamic range, low trace noise and its flexible connectivity options for testing high performance components.
Other features and specifications include:

- The operation range is from 10 MHz to 20 GHz
- 123 dB dynamic range and <0.006 dB trace noise
- 26 µs/point measurement speed, 32 channels, 16,001 points
- TRL/LRM calibration, on-wafer, in-fixture, waveguide, and antenna measurements
- Mixer conversion loss, return loss, isolation, and absolute group delay
- Amplifier gain compression, harmonic, IMD, and pulsed-RF

Windows operating system and user interface mouse makes measurement procedure much easier. In thesis, this instrument is used to measure the dielectric constant using cavity perturbation and other reflection characteristics studies.

2.2.3.3 Anechoic Chamber

The free space environment required for antenna pattern measurements is realized by the use of an anechoic chamber. The anechoic chamber provides a ‘quite zone’, free from all types of Electro-Magnetic interferences [157]. All the antenna characterizations are done in an anechoic chamber to avoid reflections from nearby objects. The absorbers used for building the chamber are made with high quality low foam impregnated with dielectrically / magnetically lossy medium. The walls are covered with carbon black impregnated polyurethene foam based pyramidal and flat absorbers of appropriate sizes. The tapered pyramidal shapes provide good impedance matching for the microwave power impinges upon it. The chamber is covered with an aluminum sheet on all the
sides to prevent external interferences. The polyurethene foam structure gives the geometrical impedance matching, while the dispersed carbon provides the required attenuation, for a wide frequency range of 1GHz to 18GHz.

2.2.3.4 Automated Turn table assembly for far field radiation pattern measurement

The turn table assembly arranged at the far field region consists of a stepper motor driven rotating platform for mounting the Antenna Under Test (AUT). The in-house developed microcontroller based antenna positioner STIC 310C is used for radiation pattern measurement. The main lobe tracking for gain measurement and radiation pattern measurement is done using this setup. A standard wideband horn (1-18GHz) is used as receiving antenna for radiation pattern measurements. The in-house developed automation software ‘Crema Soft’ built in the Matlab environment coordinates all the measurements.

2.2.4 Measurement Procedure

The experimental procedures followed to determine the antenna characteristics are discussed below. The network analyzer in real practice is connected to large cables and connectors. At higher frequencies the connector and cables have their losses, it should be avoided. Thus the instrument should be calibrated with known standards of open, short and matched loads to get accurate scattering parameters. There are many calibration procedures available in the network analyzer. Single port, full two port and TRL calibration methods are usually used. The two port passive or active device scattering parameters can be accurately measured using TRL calibration method. Proper phase delay is introduced while calibrating, to ensure that the reference plane for all measurements in the desired band is actually at 0°, thus taking care of probable
cable length variations. Using single port calibration method we can measure reflection coefficient, VSWR, input impedance etc.

2.2.4.1 Reflection coefficient, Resonant frequency and Impedance bandwidth

By choosing the single port calibration standard we can perform all these kind of measurements. The reflection characteristics of the antenna are measured by connecting the Antenna Under Test (AUT) to any one of the two ports of VNA and operating the analyzer in $S_{11}/S_{22}$ mode. The NWA is calibrated for the required frequency band and stored in the CALSET. The AUT is connected to the calibrated port. The frequency vs reflection parameter ($S_{11}/S_{22}$) values are then stored in a computer in comma separated variable (.CSV) format using the ‘Crema Soft’.

The frequency for which the return loss value is minimum is taken as resonant frequency of the antenna. The range of frequencies for which the return loss value is within the -10dB points is usually treated as the bandwidth of the antenna. Then the percentage of bandwidth of the antenna can be calculated using,

$$\%Bandwidth = \frac{bandwidth}{centrefrequency} \times 100$$

2.2.4.2 Far field radiation pattern

The measurement of far field radiation pattern is conducted in an anechoic chamber. The AUT is placed in the quite zone of the chamber on a turn table and connected to one port of the network analyzer. A wideband horn is used as a transmitter and connected to the other port of the network analyzer. The turn table is controlled by a STIC positioner controller. The automated radiation pattern measurement process is coordinated by the ‘Crema Soft’ software.
In order to measure the radiation pattern, the network analyzer is kept in $S_{21}/S_{12}$ mode with the frequency range within the -10dB return loss bandwidth. The number of frequency points are set according to the convenience. The start angle, stop angle and step angle of the motor is also configured in the ‘Crema Soft’. The antenna positioner is boresighted manually. Now the THRU calibration is performed for the frequency band specified and saved in the CAL set. Suitable gate parameters are provided in the time domain to avoid spurious reflections if any. The Crema Soft will automatically perform the radiation pattern measurement and store it as a file in comma separated variable (.CSV).

### 2.2.4.3 Antenna Gain

The gain of the antenna under test is measured along the bore sight direction, where the radiation is found to be maximum. The gain transfer method using a standard gain antenna is employed to determine the absolute gain of the AUT [158-159]. The experimental setup is similar to the radiation pattern measurement setup. An antenna with known gain is first placed in the antenna positioner and the THRU calibration is done along the boresight direction for the frequency range of interest. Standard antenna is then replaced by the AUT and the change in $S_{21}$ along the boresight direction is noted. Note that the AUT should be aligned so that the gain in the main beam direction is measured. This is the relative gain of the antenna with respect to the reference antenna. The absolute gain of the antenna is obtained by adding this relative gain to the original gain of the standard antenna.

### 2.2.4.4 Efficiency Measurement

The antenna efficiency is estimated using wheeler cap method [160] by making two impedance measurements. The antenna impedance with metallic cap and without metallic cap are measured. Since the test antenna behaves like
a series RLC circuit near its resonance, then the input resistance $R$ should decrease after applying the cap, and the efficiency is calculated by the following expression.

$$\text{Efficiency, } \eta = \frac{R_{nocap} - R_{cap}}{R_{nocap}}$$

Where $R_{nocap}$ and $R_{cap}$ are the measured resistance of the antenna without the metallic cap and with the metallic cap respectively.

### 2.2.5 Antenna Design and Optimization using Ansoft HFSS

Preliminary investigation and optimization in antenna design are done by commercially available electromagnetic simulation software’s. The simulation studies in the thesis are done using Ansoft’s High Frequency Structure Simulator (HFSS).

HFSS (High frequency Structure Simulator) is a 3D electromagnetic field simulator based on Finite Element Method for modeling arbitrary volumetric structures [161]. It integrates simulation, modeling, visualization and automation in an easy to learn environment. With adaptive meshing and brilliant graphics the HFSS gives an unparalleled performance and complete insight to the actual radiation phenomenon in the antenna. With HFSS one can extract the parameters such as $S$, $Y$, $Z$, visualize 3D electromagnetic fields (near- and far-field), and optimize design performance. An important and useful feature of this simulation engine is the availability of different kinds of port schemes. It provides lumped port, wave port, incident wave scheme etc. The accurate simulation of coplanar waveguides and microstrip lines can be done using wave port. The parametric set up available with HFSS is highly suitable for Antenna engineer to optimize the desired dimensions. The first step in
simulating a system in HFSS is to define the geometry of the system by giving the material properties and boundaries for 3D or 2D elements available in HFSS window. The suitable port excitation scheme is then given. A radiation boundary filled with air is then defined surrounding the structure to be simulated. Now, the simulation engine can be invoked by giving the proper frequency of operations and the number of frequency points. Finally the simulation results such as scattering parameters, current distributions and far field radiation pattern can be displayed. The vector as well as scalar representation of $E$, $H$, and $J$ values of the device under simulation gives a good insight into the antenna under analysis.

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Review of Literature and Methodology


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