CHAPTER 2

A BRIEF REVIEW OF PAST WORK

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This chapter gives a brief review of literature relating to microstrip antenna design in a historical perspective. The theoretical and experimental aspects of different types of microstrip antennas are covered in the first section. A review of various dual frequency microstrip antenna design techniques is given in the second section with emphasis on slot loaded patch antennas. The third section covers different reconfigurable antenna techniques employed recently in modern communication and military systems, and the emphasis is given to electronically reconfigurable microstrip antennas with semiconductor diode tuning. The final section covers various analytical and full wave solutions of microstrip antennas and reconfigurable antennas. Finite difference time domain (FDTD) analysis of various microstrip antennas is thoroughly examined in this section.

2.1 Microstrip Antenna Technology

This section describes analytical and experimental design approaches for microstrip antenna elements, and provides a comprehensive survey of the state of microstrip antenna element technology. Several practical techniques are outlined for modifying the basic element for special purpose applications such as conformal arrays and wide band communications.

The idea of planar microstrip radiators was first proposed by G. A. Deschamps [49] in USA and by Gutton and Baissinot in France [50]. Shortly thereafter, Lewin [51] investigated radiation from stripline discontinuities. Additional studies were undertaken by Kaloi in the late 1960s, who studied basic rectangular and square microstrip configurations [4]. However, work was not reported in the literature until the early 1970s, when a conducting strip radiator separated from a ground plane by a dielectric substrate was described by Byron [6]. Shortly thereafter, a microstrip antenna element was patented by Munson [7] and data on basic rectangular and circular microstrip patch antennas were published by Howell [8].
Microstrip geometries for use with cylindrical S-band arrays on rockets were later developed by Weinschel [52]. Sanford [53] showed that the microstrip element could be used in conformal array designs for L-band applications. The early works by Munson on the development of microstrip antennas on rockets and missiles showed that this was a practical concept for use in many antenna system problems, and thereby gave birth to a new antenna industry.

Mathematical modeling of the basic microstrip antenna geometries was initially carried out by the application of transmission line analogies to simple rectangular patches fed at the center of the radiating wall by Munson and Demeryd [54, 55]. Carver reported the measurements and analysis of the radiation pattern of a circular patch microstrip antenna [56]. Although the transmission line model is easy to use, it suffers from numerous disadvantages. It is only useful for patches of rectangular shape, and an unknown constant called fringe factor must be empirically determined, it ignores field variations along the radiating edge and it is not adaptable to the inclusion of the feed. These limitations are eliminated in the modal expansion analysis.

Lo et al [57] in 1977 published the modal expansion technique to analyze rectangular, circular, semicircular and triangular patch geometries. Here the patch is considered as a thin cavity with leaky magnetic walls. The impedance boundary conditions are imposed on the four walls and the stored and radiated energy were investigated in terms of complex wall admittances. Similar analytical papers on basic patch geometries were later published by Derneryd [58], Chen and Long [59], and Carver and Coffey [60]. Thus by 1978, the microstrip patch antenna became much more widely known and used in a variety of communication systems. This was accompanied by increased attention by the theoretical community to improved mathematical models which could be used for design.
As the microstrip antenna technology developed further, many new substrate materials were also invented with dielectric constants ranging from 1.17 to 25 and loss tangents from 0.0001 to 0.004. A comparative data on most available substrates were later published by Carver and Mink [4].

The basic microstrip antenna geometries like rectangular and circular have been modified to other shapes such as pentagon and hexagon [11, 61]. For these geometries the modal expansion technique is a more cumbersome analysis method than a direct numerical method, due to the difficulty in finding the appropriate orthogonal mode vectors. In recent years several numerical techniques applied to the microstrip antenna have been proposed, including the method of moments by Newman [62, 63], the uni-moment Monte Carlo method [64], the finite element techniques [60], and the direct form of network analogs method [65]. The effect of radiation and other losses are represented in terms of either an artificially increased substrate loss tangent or by the more elegant method of impedance boundary conditions at the walls [66, 67]. The method of moments is used in connection with Richmond's reaction method [68] to determine the unknown surface currents flowing on the walls forming the microstrip patch, ground plane and magnetic walls.

The transmission line model, cavity model and the multi-port network model all come under the reduced analysis category, which uses one or more significant approximations to simplify the problem. The multi-port network model generalizes the cavity model [69]. Drawbacks of these models include limited accuracy for resonant frequency and input impedance for substrates that are not very thin [70], and their limited capacity to handle related problems such as mutual coupling, large arrays, surface wave effects and different substrate configurations.

The numerical analysis of the fields interior to the microstrip antenna cavity can also be carried out using a finite element approach [60]. This is a variational
method in which a minimization process automatically seeks out the solution which is closest to the true analytical solution.

Deshpande and Bailey [25] used the spectral domain full wave approach which uses the exact Green's function for the mixed dielectric nature of the microstrip antenna. Various patch geometries and feed structures were analyzed using this technique. The analysis of a rectangular patch and a circular disc were studied by Chew, Aberle and Bailey [71-73].

In addition to standard rectangular and circular patch antennas, several modified patch geometries were developed by researchers for different applications. One of the requirements is the generation of circular polarization. Various shapes for microstrip antennas capable of circular polarization operation have been reported in literature [74, 75]. Design of circularly polarized patch antennas fabricated on ferrite substrate was demonstrated by Tsang and Langley [76].

In 1981 rigorous experimental studies were carried out by Schen [77] and Long [78] on elliptical shaped printed antennas with circular polarization generation. Later in 1988, Haneishi and Yoshida [79] designed a circularly polarized rectangular microstrip antenna with a single point feed. Huang [80] used an array of linearly polarized elements to obtain circular polarization.

The serious limitation of narrow bandwidth of microstrip antennas was fixed by researchers using a variety of innovative patch designs and feed modifications. Pozar [81] proposed the aperture coupling of microstrip patch antennas for improved impedance bandwidth and reduced spurious radiation. Basic aperture coupled patch antenna geometries were analyzed using various techniques including the integral equation method [82-85], cavity model [86-88], transmission line model [89, 90] and modal expansion method [91].
The use of stacked patches in order to increase the impedance bandwidth was first proposed by Long and Walton [29]. Here an upper patch with a slightly different dimension was proximity coupled to the lower excited patch. Impedance bandwidth up to 30% had been achieved with probe fed stacked patches [92, 93] and up to 67% for aperture coupled stacked patches [94, 95]. The larger bandwidth in each case corresponds to relatively thicker substrate.

A set of coplanar resonators with slightly different resonant frequencies were used by Kumar, Entsehladen and Aanandan to obtain broadband performance [96-98].

Pues and Van de Capelle [99] obtained a bandwidth of about 12% using a passive coplanar matching network. Similar techniques used by Paschen [100] produced a bandwidth of more than 25%, which was sufficient to cover the GPS bands with a single radiating element.

Wong and Lin [101] studied the loading effect of a chip resistor mounted at the edge of a rectangular patch. The 10dB return loss bandwidth of this patch antenna was found to be about 4.9 times that of a patch without the resistor loading [102].

As the telephone handsets for mobile communications needed compact antennas, several designs were proposed to reduce the size of existed microstrip patches. In 1989, Kossiavas et al [103] proposed a small C-shaped patch element for applications at 413MHz.

Vandenbosch in 1995 [104] presented a capacitive matching of small microstrip antennas with rigorous theoretical analysis to calculate the input impedance. This method allows separation of the analysis of the capacitive feeding from the analysis of the radiating patch. Later in 1997, Corbett and Murch [105], proposed a capacitively loaded planar inverted F- antenna (PIFA) for mobile telephone handsets. They found the capacitive load reduces the resonance length of the PIFA from $\frac{\lambda}{4}$
to less than $\frac{\lambda}{8}$. A design with a bandwidth of 178MHz centered at 1.8GHz was provided to demonstrate that compact antennas for mobile telephone handsets can be constructed using this approach.

K. L. Wong and Cheng Pan in 1997 [106] used a shorting pin in a triangular microstrip patch fed with a coaxial probe, to reduce its size at 1.9GHz band. They obtained a reduction of 78% in the linear dimension of the microstrip antenna.

Different slot loaded patch geometries were suggested by this time to make the conventional microstrip patch antennas more compact. The addition of shorting pins and chip resistors further brought down the size. J. H. Lu et al [107], in 1997 proposed a slot coupled triangular microstrip patch antenna with a shorting pin or chip resistor loading. This technique of chip resistor loading provided a much broader operating bandwidth as compared to regular patches or shorted patch antennas.

Small broadband rectangular microstrip patch antenna with a chip resistor at its edge was proposed by K. L. Wong and Y. F. Lin [108], for increased bandwidth and size reduction. The design was applicable to both probe fed and microstrip line fed antenna configurations.

C. Y. Huang et al [109] reported a broadband circular polarization operation of a single feed slot coupled microstrip antenna using an inclined nonlinear coupling slot. This nonlinear slot, end loaded with two V-shaped slots, significantly broadens the bandwidth to about 2.1 times that obtained using a simple inclined coupling slot.

A novel folded rectangular microstrip patch antenna was designed by K. M. Luk et al [110]. Compared with a conventional pat antenna with the same surface area, the resonant frequency was reduced by 37%. The cross-polarization level was also near -20dB.
Wen Hsu [111] investigated a novel disk sector microstrip antenna with specific flare angles for circular polarization operation. Their results showed that by suitably selecting the flare angle of the disk sector microstrip patch, right hand or left hand circular polarization can easily obtained using a single coaxial probe feed.

S. K. Satpathy et al [112], studied different shorted variations of triangular microstrip patch antennas. The increased size reduction was achieved by partially shorting the curved edges of the sectoral antennas.

A novel two layer rectangular patch antenna had been designed and tested with a 5% bandwidth by R. Chair et al [113]. Compared with a basic single layer patch antenna with the same projection area, the resonant frequency was reduced by 39%.

Bandwidth enhancement of a single layer, single patch rectangular microstrip patch antenna was achieved by J. Y. Sze et al [114], by embedding a pair of double bent slots close to the patch's non-radiating edges and an additional bent slot centered to the patch's center line. An antenna bandwidth up to about 2.8 times that of a conventional unslotted rectangular patch had been obtained.

C. S. Hong [115] designed a small size annular slot antenna with miniaturized slot shrunk by a loaded capacitor. The antenna had the advantages of a good impedance bandwidth and good linearly polarized radiation patterns after chip capacitor loading. A 23.4% slot antenna area size reduction had been achieved with this type of capacitor loading compared with the ordinary slot antenna.

M. C. Liang et al [116] proposed a frequency varying microstrip patch antenna design with a loaded capacitor. Unlike traditional patch size reduction schemes, this capacitor - loaded design does not significantly affect the radiated power efficiency of the antenna. In some cases the maximum radiated power can even be improved.
A novel internal square microstrip patch antenna for 3G IMT – 2000 mobile handsets was first investigated by Y. J. Wang [117]. By introducing a single shorting pin and a thin rectangular slot perforated in a square patch, this probe fed antenna realized an impedance bandwidth of 25.6% with dual frequency operation, which thoroughly covers the 3G IMT – 2000 frequency spectra.

In 2001, Jaume Anguera et al [118] proposed a systematic design method for broadband single patch antenna input impedance prediction. This mathematical approach allowed designing an optimum feed that enhances the impedance bandwidth.

J. P. Lee and S. O. Park [119] in 2002 put forward a small size and high gain meander line antenna for Bluetooth applications. The bandwidth of this design was about 9% at 2.44GHz and the gain was 2.73dBi. They achieved a size reduction of 35% compared to conventional patch antennas.

A novel and broadband semi disk microstrip antenna suitable for a portable and compact terminal integrated with the 3G IMT-2000 cellular system, DECT mobile system, and Bluetooth wireless technology was discussed both theoretically and experimentally by Y. J. Wang [120]. The reduced dimensions of the proposed antenna were achieved by using a single cylindrical shorting pin, while the broadband characteristics were obtained through a narrow rectangular slot which induced two resonant frequencies sufficiently close to each other.

Aaron Shackelford et al [121] in 2003 examined several designs for small size widebandwidth microstrip antennas. The designs were presented based on a U-slot patch and an L-probe-fed patch. Several techniques were utilized to reduce the resonant length of these wideband microstrip patch antennas: increasing the dielectric constant of the microwave substrate material, a shorting wall or shorting pin between the conducting patch and the ground plane. A size reduction of 94% and bandwidth of 20% were attained by these techniques.
A numerically efficient substitute for the general transmission line model of microstrip antennas was suggested by S. K. Roy [122] in 2000. Here the fringe factor determines the accuracy of the resonant frequency calculation. In 2004, Schubler, Jens Freese and Jakoby [123], derived design equations for compact planar antennas using LH – transmission lines. This model allows preliminary design studies and was able to improve the understanding of the connection between bandwidth and radiation impedance.

2.2 Dual Frequency Microstrip Antenna Design

Dual frequency microstrip patch antennas may provide an alternative to large bandwidth planar antennas, in applications in which large bandwidth is really needed for operating at two separate transmit-receive bands. On the other hand, modern communication systems, such as those for satellite links (GPS, Vehicular etc.), as well as emerging applications like wireless local area networks (WLAN), often require antennas with compactness and low-cost, thus rendering planar technology useful, and sometimes unavoidable. Furthermore, thanks to their lightness, patch antennas are well suitable for systems to be mounted on airborne platforms, like synthetic aperture radar (SAR) and scatterometers. Despite the convenience that they may provide in terms of space and cost, not much importance has been given to dual frequency microstrip antennas. This is possibly due to the relative complexity of the feeding network which is required, in particular for array applications. An excellent review of dual frequency microstrip antennas was given by S. Maci and Biffi Gentili [34] in the year 1997.

Wang and Lo [124] were the first to use shorting pins and slots in a rectangular microstrip patch to generate dual frequency operation. The upper and lower frequencies showed similar broadside radiation characteristics.
In 1993, Yazidi et al [88] designed an aperture coupled rectangular microstrip patch antenna with a pair of symmetrical slots. The excited modes of the antenna depend on the type and position of the feed. By choosing aperture coupling with a centered slot, the even modes were not excited.

If two orthogonal linear polarizations at separate frequencies are required, the simplest antenna for this is a rectangular patch antenna fed at the diagonal for exciting the (1, 0) and (0, 1) modes. The frequencies of these modes are determined by the respective lengths of the patch. Impedance matching for these two resonant frequencies can be easily achieved with a single feed. Salvador et al [125], proposed a new configuration of dual frequency planar antenna operating at S and X bands. They used a cross patch sub array and the geometry had two symmetry planes to provide radiation in double-linear polarization by using a proper feeding system.

K. L. Wong and G. B. Hsieh [126] suggested a dual frequency circular microstrip antenna with a pair of arc shaped slots excited with a single co-axial feed. Frequency ratio ranging from 1.38 to 1.58 were implemented and studied.

A slot loaded bow-tie microstrip antenna for dual frequency operation was proposed by K. L. Wong and W. S. Chen [127]. Frequency ratios within the range 2 to 3 were obtained with a single probe feed.

Chen [128] demonstrated a single probe fed dual frequency rectangular microstrip antenna with a square slot at its center. This technique was one of the simplest methods of dual frequency generation in a rectangular patch with dual linear polarization. The excited frequencies were orthogonally polarized.

E. Lee et al [129] developed a compact dual-band dual-polarization microstrip patch antenna for application in terrestrial cellular communication and satellite mobile. The two operating frequencies showed different polarization and radiation characteristics. Bandwidths of 2 and 4% respectively, had been obtained in the two resonant modes.
J. H. Lu [130] demonstrated a dual-frequency rectangular microstrip patch antenna with embedded spur lines and integrated reactive loading. The two operating frequencies had the same polarization planes and frequency ratios of 1.1 to 1.6 were achieved with a single feed.

Jui-Han Lu [131] described novel dual-frequency design of single feed equilateral triangular microstrip antenna having same polarization planes and similar radiation characteristics.

Guo et al [132] demonstrated a dual band patch antenna using slot loaded and short-circuited size reduction techniques. By controlling the short plane width, the two resonant frequencies can be significantly reduced and the frequency ratio was tunable in the range 1.6 to 2.2.

A slot loaded dual-frequency rectangular microstrip patch antenna with a single feed was also proposed by J. H. Lu [133]. By varying the angle and the horizontal section length of the bent slots, the frequency ratio was tunable in a range from about 1.28 to 1.79.

X. Yang [134] derived analytical expressions for the input and mutual impedance of two kinds of dual-polarization square-patch antenna double fed at the orthogonal edges using the Green's function approach based on the planar circuit principle. The frequency characteristics of the input impedance, VSWR and isolation were analyzed and verified by experimental data.

C. Tang et al [135] designed a broadband dual frequency V-shape microstrip patch antenna with impedance bandwidths up to 10%.

A dual band GSM - 900/DCS - 1800, personal communication handset microstrip antenna with a spur-line filter and a shorting pin was proposed by M. M. Vazquez et al [136]. It consists of a PIFA like rectangular patch with a shorting pin close to
the corner of the patch. The spur line generated a second resonant mode lower than that of the rectangular patch.

A slot coupled chip capacitor loaded square microstrip patch antenna for dual frequency operation was proposed by G. S. Binoy et al [137]. The design provided an enhanced area reduction of 64 and 36% respectively, for the two operating frequencies and good cross-polarization levels.

2.3 Reconfigurable Antenna Techniques

With ever increasing demand for reliable wireless communications, the need for efficient use of electromagnetic spectrum is on the rise. Conventional broadband antennas discussed above never satisfy all these demands. The reconfigurable antennas have shown strong potential in this field due to its low cost and flexibility. This section depicts the recent advancements in reconfigurable antenna technology.

In 1991, Kawasaki and Itoh [138] demonstrated a novel idea of electronic tuning with the help of integrated FET components in a microstrip slot antenna. By changing the bias voltages, the reactance of the FET varied and the length of the slot was tuned electronically. 10% tuning of the center frequency was obtained with negligible changes in the radiation pattern. The 50 Ω matching point of the center feed line was difficult to maintain, since the reactive circuits made of MESFETs affected the field distribution of the slot antenna.

Rainville and Harackiewicz [139] proposed a magnetic tuning scheme for a single feed square microstrip patch antenna fabricated on a ferrite film. The application of a small in-plane magnetic field tuned the frequency and the phase of one of the polarization.

The bandwidth extension approaches in tunable dipole antennas were illustrated by D. J. Roscoe et al [140] in 1993. They integrated beam lead diodes to the original
printed dipole and its parasitic patches so as to present low or high impedances according to its bias states. This produced a multi frequency antenna which was controlled by an applied bias voltage.

Egor Alekseev et al [141], invented InGaAs/InP PIN diodes for microwave and millimeter wave switching and limiting applications. DC and microwave characterization of the PIN diodes demonstrated low turn-on voltage (0.46 V), low insertion loss (<1.2dB up to 38GHz) and high switching cut-off frequency (17THz) as necessary for microwave and millimeter – wave switching and limiting applications.

M. A. Forman and Z. B. Popovic [142] designed a tunable second – resonance cross – slot antenna for use in active array applications. The resonant frequency can be mechanically tuned over a 45% bandwidth or electrically tuned over a 10% bandwidth with an integrated varactor diode.

A varactor loaded electronically tunable microstrip patch antenna with a probe feed was presented by S. H. Al-Charchafchi and M. Frances [143]. An effective impedance bandwidth of 50% was achieved centered on a frequency of 2.2GHz. A simple transmission line model was used to predict the resonant frequency.

Various radio frequency applications involving microelectromechanical systems (MEMS) were studied thoroughly by Elliott R. Brown [144] in 1998. RF MEMS are the new class of passive devices (e.g. switches) and circuit components (e.g. tunable transmission lines) controlled by MEMS. Several applications of these types of switches were analyzed here, including switchable routing in RF system front-ends and time-delay networks. The promising concept of reconfigurable antennas controlled by these MEMS was discussed in detail.

N. Fayyaz et al [145] designed a novel electronically tunable rectangular patch antenna with one octave bandwidth for applications in multi-band communication
systems and frequency hopping systems. The layout of the antenna consisted of a rectangular patch antenna divided into two sections and connected using varactor diodes. However, a wide tuning range resulted in mismatching in a larger range of frequencies because the feed point was fixed mechanically.

Kolsrud et al [146] proposed a dual-frequency electronically tunable CPW-fed coplanar strip dipole antenna with varactor control. Dual frequency operation of the dipole antenna was realized by introducing a small gap in the length of the dipole. Varactors were integrated with this dipole to tune the antenna, by applying reverse bias. But a wideband CPW-to-CPS balun was needed to feed the antenna in order to achieve better matching.

S. Sharma and B. R. Vishvakarma [147] studied a new MOS capacitor loaded frequency agile microstrip patch antenna in which the operating frequency of the rectangular microstrip antenna was electronically controlled by the bias voltage of the MOS capacitor. Theoretical investigations based on a modal expansion cavity model were carried out for different MOS structures. The larger frequency variation was achieved with lower variation in the bias voltage as compared with the varactor diode.

MEMS-switched reconfigurable multi-band antenna design and modeling were thoroughly studied by W. H. Weedon et al [148] in 1999. A general adaptive reconfigurable feed design methodology was proposed for designing and tuning the feed structure for each configuration independently. However, their research was limited to simulating the MEMS switches as ideal switches, and building separate antennas to simulate the OPEN and CLOSED configurations.

B. C. C. Chang et al [149] developed a reconfigurable leaky mode patch antenna controlled by PIN diode switches. Different radiation configurations were obtained by switching the antenna with PIN diodes. When the switches were turned on, the
entire microstrip structure functioned as a leaky mode antenna, while, when the switches were turned off, the segmented pieces of microstrips converted into ordinary patch antennas.

A prototype of a reconfigurable patch module array connected using MEMS switches were proposed by W. H. Weedon et al [150] for dual band application in L and X bands. Stripline power dividers and blind via transitions were developed to demonstrate feed structures that could be located below the radiating aperture.

Fan Yang and Y. Rahmat-Samii [151] put forward the concept of a patch antenna with switchable slot for dual frequency operation. A slot was incorporated into the patch and a PIN diode was utilized to switch the slot on or off, for achieving dual frequency operation. The antenna was designed for same polarization at two frequencies and for a small and flexible frequency ratio. Similar radiation patterns were observed at the two operating bands.

A planar microstrip line fed reconfigurable slot antenna with a series of PIN diode switches were proposed by D. Peroulis et al [152]. The tuning of the operating frequency was realized by varying the electrical length of the slot using the loaded PIN diodes. The antenna was capable of radiating at four different frequencies ranging from 550 to 900 MHz. Unlike other reconfigurable antenna designs discussed earlier, this configuration never used any special matching network. It was demonstrated that the radiation pattern, efficiency and polarization remained essentially unaffected by the frequency tuning.

F. Yang and Y. Rahmat-Samii [153] devised a novel reconfigurable patch antenna using switchable slots for circular polarization diversity. Two orthogonal slots were incorporated into the patch and two pin diodes were utilized to switch the slots on or off. Right hand and left hand circular polarizations were generated by suitably
switching the diodes on and off. The design was well suitable for wireless communication applications and future planetary missions.

The influence of the PIN diode bias current on the microstrip reconfigurable antenna efficiency was studied by J. M. Laheurte et al [154]. A drop in radiation efficiency was observed for inadequate values of the PIN diode bias current. A trade off between the dc – consumption of the diodes and the antenna gain was demonstrated. A simple resistor model was used for the TLM analysis of the antenna.

G. H. Huff et al [155] illustrated a novel radiation pattern and frequency reconfigurable single turn square spiral microstrip antenna. The basic antenna at 3.7GHz operates with a linear polarization. One set of connections provided a redirected radiation pattern while maintaining a common operating impedance bandwidth. The second set of connections resulted in an operation at a higher band at 6GHz with broadside patterns.

Aly Fathy et al [156] reported an innovative reconfigurable antenna concept with significant practical relevance based on dynamic definition of metal-like conductive plasma channels in high resistivity silicon that were activated by the injection of dc-current. These dynamically defined plasma reconfigurable antennas enable frequency hopping, beam shaping and steering without the complexity of RF-feed structures.

W. H. Chen et al [157] proposed a dual-band planar-reconfigurable antenna for wireless communications. The concept of pattern steering in several given directions was demonstrated using ideal switches.

The design of reconfigurable slot antennas was well illustrated by D. Peroulis et al [158]. A single-fed resonant slot antenna, loaded with a series of PIN diode switches constitutes the fundamental structure. An effective bandwidth of 1.7:1
was obtained through this tuning without using a reconfigurable matching network. The radiation pattern, efficiency and polarization remained essentially unaffected by the frequency tuning.

2.4 Analysis of Microstrip Antennas

Various analytical and full wave methods for the analysis of microstrip antennas were already discussed in sections 1.1.3 and 1.4. Among them, the finite difference time domain (FDTD) method is arguably the most popular numerical method for the solution of problems in electromagnetics.

Reineix and B. Jecko [159] were the first to apply the FDTD method to the analyses of microstrip antennas. Modifications had been made on the classical FDTD method in order to study the microstrip antennas. All frequency dependent parameters of a rectangular microstrip patch antenna were predicted using this method.

Leveque et al [160] modeled frequency dispersive microstrip antennas while Wu et al [161] used the FDTD method to accurately measure the reflection co-efficient of various microstrip antenna configurations.

Uehara and Kagoshima [162] presented an analysis of the mutual coupling between two microstrip antennas while Oonishi et al [163] and Kashiwa et al [164] used one of the conformal FDTD approaches to analyze microstrip antennas on a curved surface.

In 1992, Luebbers et al [165] and Chen et al [166] analyzed hand-held antennas using an FDTD model of a monopole antenna on a conducting or dielectric box. Sheen et al [167] presented FDTD results for various microstrip structures, including a rectangular patch antenna, a low-pass filter and a branch line coupler.
In 1995, Bilge Belentepe [168] derived a simple equivalent circuit model to represent an electromagnetically coupled microstrip patch antenna. This model allows the use of different dielectric constants for the substrate on which the patch and the microstrip line were printed.

D. Lee and S. Lee [169] proposed a design of a coaxially fed circularly polarized rectangular microstrip patch antenna using a genetic algorithm. They derived the objective function from the cavity model and optimized the size and feeding point of the antenna using the genetic algorithm.

H. T. Chen and K. L. Wong [170] analyzed probe-fed spherical-circular microstrip antennas using cavity model theory. Theoretical formulation of the input impedance and far-field radiation were discussed in detail.

D. L. Sengupta [171] used a uniform transmission line model to determine the resonant frequency of a coaxial probe-fed rectangular patch antenna tuned by a number of passive metallic posts suitably placed within the antenna boundary. An approximate expression was given for the resonant frequency as a function of the post location and number, and other characteristic parameters of the antenna.

B. Beker et al in 1994 [172] proposed quasi-static electromagnetic models for analysis and design of microwave capacitors and integrated circuit packages. The theoretical background for modeling of open 3-D boundaries with finite difference method was reviewed thoroughly in this paper.

Radiation and scattering analyses of a slot-coupled patch antenna loaded with a MESFET oscillator was verified by C. C. Huang and T. H. Chu [173]. In the analysis, the antenna was represented by its equivalent circuit model based on the reciprocity theorem and method of moments. A circuit equation of the MESFET oscillator was then analyzed using the Volterra series technique to acquire the oscillating frequency and the output radiation power.
Luebbers and Langdon [174] demonstrated a simple feed model that reduces time steps needed for FDTD antenna and microstrip calculations. The approach was based on using a source with an internal resistance to excite the problem.

Mehmet Kara [175] derived formulas for the computation of the far-field radiation patterns of rectangular microstrip antenna elements with thick substrates. Three closed form formulas were presented for the calculation of the E-plane radiation pattern, derived from two-slot models. The H-plane pattern was calculated from both two-slot and cavity models.

K. M. Krishnaiah and C. J. Railton [176] proposed a novel method of updating the sub-grid boundary fields by replacing the grid discontinuity with an equivalent circuit. The stability and accuracy of this new scheme was demonstrated through calculation of the cut-off wavelength of a dielectric slab loaded waveguide for various slab thickness.

M. J. White [177] developed a novel multi-grid FDTD code for three-dimensional applications which focuses a large number of cells of small dimensions in the region of interest. The simulation required the construction of two grid regions; a coarse-grid region and a fine-grid region surrounding the area of interest.

F. Bilotti et al [178] designed a multi-frequency patch antenna using a combined numerical procedure with method of moments and genetic algorithm. Method of moments was applied to analyze rectangular patches fed by a coaxial probe and suspended over a ground plane. Then the impedance matrix of such a structure was manipulated by a genetic algorithm optimization procedure.

A simple and efficient method to incorporate non-linear bipolar junction transistors (BJT) into finite difference time domain (FDTD) framework was presented by F. Kung and H. T. Chuah [179].