Chapter 2

REVIEW OF LITERATURE AND METHODOLOGY

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This chapter presents the results of previous investigative works, as well as the literature of the antenna structure in a historical perspective. A comprehensive survey of the state of microstrip antenna technology is covered in the first section. A review of various reconfigurable antenna techniques employed in modern communication systems, with an emphasis to frequency and polarization reconfigurable antennas using PIN diodes and varactors are discussed in the following section. The simulation, fabrication and measurement procedures utilized for characterizing the antennas are discussed in the next section. The antenna simulation studies and parametric analysis are carried out using Ansoft High Frequency Structure Simulator (HFSS). The prototype of the different antenna geometries were fabricated using photolithographic process and measurements are carried out at our test facility consisting of vector network analyzer and anechoic chamber. The chapter concludes with a concise description of the measurement techniques employed to analyze the experimental results.
2.1 Microstrip antenna technology

The present research in printed antenna technology points to the development of antennas which cater the need of low profile, compact communication gadgets. The antenna designers around the world are concentrated in the design of compact antennas with efficient radiation characteristics. The following modules provide a comprehensive survey about the developments in the state of art printed antenna technology around the world. This section provides a comprehensive survey of the state of microstrip antenna technology.

Even though G. A. Deschamps, USA first proposed the concept of a microstrip radiator in 1953 [1], Gutton and Baissinot in France [2] acquired a patent in 1955. 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 [3]. The first practical antennas were developed by Howell [4]. Yoshimura et al. proposed a microstrip line slot antenna and a two-dimensional Dolph-Chebyshev slot-array antenna at X-band frequency [5]. Microstrip line slot antennas appear to be quite useful in various fields of application because of their savings in cost, size and weight. Microstrip antennas constitute a new class of omni-directional antenna for missiles and satellites. These antennas are capable of producing nearly perfect omni-directional coverage. A new low-cost low profile flat microstrip arrays by Munson [6-8] has 90-percent aperture efficiency. Design procedures for both linear and circular polarized antennas from UHF through C band were published by Howell [9].

Derneryd derived an equivalent network for square and rectangular shaped microstrip radiating elements [10]. The resonant frequency in analytical
form for a planar, circular disc antenna which is etched on a printed-circuit board so that the low-profile antenna is separated from the ground plane only by a thin layer of dielectric material was derived by L. C Shen et al. [11]. The formula is found to have an error of less than 25 percent when compared with experimental data. James et al. proposed a new design technique for linear microstrip microwave arrays [12]. Open-circuit terminations on half-wavelength stubs form the radiating elements. The usefulness of the new design technique has been demonstrated for both resonant and travelling-wave elements and ancillary problems, involving radomes, corporate feeds and the novelty of being able to direct the beam to broadside in the travelling-wave antenna. Another method to analyze a microstrip antenna is presented by Pradeep et al. [13]. It involves representing the antenna by a fine wire grid immersed in a dielectric medium and then using Richmond's reaction formulation to evaluate the piecewise sinusoidal currents on the wire grid segments. The calculated results are then modified to account for the finite dielectric discontinuity. A comparison of calculated and measured results was presented. This technique will serve as an excellent tool to design microstrip antennas. Theoretical and experimental works on the radiation characteristics of microstrip antennas have been done at microwave frequencies by Chatterjee et al. [14] and Lewin [15]. A method for altering the resonant length of a square microstrip antenna was described by Chowdhury et al. [16].

The relevant analysis and computations have been carried out to propose a possibility of realizing a microstrip antenna having comparatively smaller dimensions and larger bandwidth. The theoretical modeling of the microstrip antennas was carried out by Derneryd [17]. The input impedance as a function of the feed point is calculated by considering the element as a line resonator with the open-circuited terminations modeled as an RC network. From a
radiation point of view the element is treated as two narrow slots, one at each end of the line resonator. The interaction between the two slots is considered by defining a mutual conductance. From the far fields, the directivity of a patch and the mutual conductance between patches are calculated. The analysis of the pattern and impedance loci of microstrip antennas developed by Richards et al. yields a theory that is simple and inexpensive to apply [18]. This is achieved by lumping all antenna losses into an effective dielectric loss tangent and then analysing the microstrip antenna as a lossy cavity. It is found that the resulting expression for impedance of the microstrip antenna is in good agreement with measured results for all modes and feed locations.

Krali et al. developed an omni microstrip antenna which is a microstrip-shorted quarter-wave resonator that is wrapped around a cylinder [19]. It is an electrically short antenna, and it can be made to radiate an omnidirectional pattern normal to the axis of the cylinder. Equations governing the design of the antenna are given along with a method of excitation. Lo et al. in 1979 developed a simple theory based on the cavity model to analyze microstrip antennas [20]. In general the theoretically predicted radiation patterns and impedance loci closely agree with those measured for many antennas of various shapes and dimensions investigated. In fact, this theory enables the computation of both patterns and impedance loci with little effort. The input admittance locus generally follows a circle of nearly constant conductance, but its center is shifted to the inductive region in the Smith chart plot. Peculiar properties for the case with degenerate or slightly degenerate eigen values are discussed. An accurate formula for determining the resonant frequency of a rectangular microstrip antenna is also given. Many variations of this method have been used to analyze the microstrip antenna [21-23].
The numerous advantages of microstrip antenna, such as its low weight, small volume, and ease of fabrication using printed-circuit technology, led to the design of several configurations for various applications [24-25]. With increasing requirements for personal and mobile communications, the demand for smaller and low-profile antennas has brought the microstrip antenna to the forefront. Microstrip antennas have narrow bandwidth, typically 1–5%, which is the major limiting factor for the widespread application of these antennas. Increasing the bandwidth of microstrip antennas has been the major thrust of research in this field [26-32]. The microstrip antenna can be excited directly either by a coaxial probe or by a microstrip line. It can also be excited indirectly using electromagnetic coupling or aperture coupling and a coplanar waveguide feed, in which case there is no direct metallic contact between the feed line and the patch [33-36]. Feeding technique influences the input impedance and characteristics of the antenna, and is an important design parameter.

The regular microstrip antenna configurations, such as rectangular and circular patches have been modified to rectangular ring [42] and circular ring [43], respectively, to enhance the bandwidth. The larger bandwidth is because of a reduction in the quality factor Q of the patch resonator, which is due to less energy stored beneath the patch and higher radiation. When a U-shaped slot is cut inside the rectangular patch, it gives a bandwidth of approximately 40% for VSWR ≤ 2 [44]. Similar results are obtained when a U-slot is cut inside a circular or a triangular microstrip antenna [45-46].

2.2 Dual-frequency microstrip antennas

Dual-frequency planar antennas should operate with similar features, both in terms of radiation and impedance matching, at two separate frequencies. Obtaining these features by using planar technologies is not a straightforward
matter, particularly when the intrinsic structural and technological simplicity of patch antennas is to be preserved. Dual-frequency 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. When the two operating frequencies are far apart, a dual-frequency patch structure can be conceived to avoid the use of separate antennas. Dual-frequency antennas exhibit a dual-resonant behavior in a single radiating structure.

Modern communication systems, such as GPS, vehicular, as well as emerging applications such as wireless local 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. From these applications, a new motivation is given for research on innovative solutions that overcome the bandwidth limitations of patch antennas. In applications in which the increased bandwidth is needed for operating at two separate sub-bands, a valid alternative to the broadening of total bandwidth is represented by dual-frequency patch antennas. Despite the convenience that they may provide in terms of space and cost, little attention has been given to dual-frequency patch antennas. This is probably 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 in the year 1997 [47-48].

Wang and Lo 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 1987, J. S.
Dahele \textit{et al.} presented experimental results of a dual-frequency microstrip antenna [49] consisting of two stacked annular rings of outer radii 5 cm and inner radii 2.5 cm fabricated on a duroid substrate with relative permittivity 2.32 and thickness 0.159 cm. The separations of the two resonant frequencies range from 6.30-9.36 percent for the first three modes. The frequency separations can be altered by means of an adjustable air gap between the lower ring and the upper substrate. A novel microstrip antenna has been proposed by C. S. Lee \textit{et al.} to operate at dual frequencies [50]. The non-radiating edges of a microstrip patch are closed with a conducting foil. Resonant frequencies are altered by varying the air gap under the patch. The separation of the resonant frequencies can be nearly zero and has no upper limit in principle. The input impedance is easily matched by shifting the air gap. The radiation patterns are not affected by modification for dual-frequency operation.

If two orthogonal polarizations at separate frequencies are required, the simplest antenna for this is a rectangular patch 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 \textit{et al.} [51], 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 symmetric planes to provide radiation in double-linear polarization by using a proper feeding system. Dual-frequency operation of a triangular microstrip antenna is proposed by S. C. Pan \textit{et al.} using a shorting pin and fed by a single probe feed [52]. By varying the shorting-pin position in the microstrip patch, such a design can provide a large tunable frequency ratio of about 2.5–4.9 for the two operating frequencies. K. L. Wong and G. B. Hsieh [53] 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 [54]. Frequency ratios within the range 2 to 3 were obtained with a single probe feed. A single probe fed dual frequency rectangular microstrip antenna with a square slot at its center is demonstrated by Chen [55]. This was one of the simplest methods of dual frequency generation in a rectangular patch with linear orthogonal polarization. A compact dual band dual polarization microstrip patch antenna for terrestrial cellular communication and satellite mobile was developed by E. Lee et al. [56]. The two operating frequencies showed different polarization with bandwidths of 2 and 4% respectively. J. H. Lu demonstrated a rectangular microstrip patch antenna [57] with embedded spur lines and an equilateral triangular microstrip antenna [58] for dual frequency operation. The two operating frequencies had the same polarization planes and frequency ratios 1.1 to 1.6 were achieved with a single feed.

A dual band slot loaded short circuited patch antenna was proposed by Guo et al. [59]. By controlling the shorting plane width, the two resonant frequencies can be significantly reduced and the frequency ratio was tunable in the range 1.6 to 2.2. J. H. Lu [60] proposed a slot loaded dual frequency rectangular microstrip antenna with a single feed. By varying the angle and the horizontal length of the bent slots, the frequency ratio was tunable in a range from 1.28 to about 1.79. M. Yang et al. analyzed and optimized the electric performance of a U-shaped dual-frequency single feeding port planar inverted-F microstrip antenna [61-62] for mobile communication applications in both the GSM and DCS 1800 systems by means of the generalized non-uniform finite-difference time-domain (NU-FDTD) Maxwell’s solver.
G. S. Binoy et al. [63] proposed a slot coupled chip capacitor loaded square microstrip patch antenna for dual frequency operation. This design provides an enhanced area reduction of 64% and 36% respectively, for the two operating frequencies with good cross polarization levels. A dual-frequency electric–magnetic–electric (EME) microstrip [64] exhibiting two leaky-wave regions of similar radiation characteristics like the microstrip patch is proposed by Y. C. Chen et al. The EME microstrip incorporates a photonic band gap (PBG) structure, which is a two-dimensional array consisting of unit cell made of coupled coils connected by via. The PBG structure employed in the EME prototype conducts at dc and shows the first stop band between 8.8–12.4 GHz, thus rendering the so-called magnetic surface. The EME microstrip is essentially made by substituting the PBG cells for the metal strip of a conventional microstrip. The finite-element method (FEM) analyses of the PBG structure show that the first and second modes are TM-like and TEM-like, respectively. The latter is leaky between 12.4–12.9 GHz and is found to be responsible for the second leaky region of the EME microstrip. The dispersion characteristics of the EME microstrip are obtained by two theoretical methods, namely, the matrix-pencil method and the FEM. Both show excellent agreement in the two leaky regions.

Jen-Yea Jan demonstrated a novel dual-frequency design of a single-layer single-feed circular microstrip antenna with an offset open-ring slot [65]. By selecting a suitable radius of the circular patch enclosed by this offset open-ring slot, a dual-frequency operation with its two operating modes excited with the same polarization planes is obtained. The frequency ratio of the two frequencies is within a range of about 1.22 to 2.17. The measured results show that similar broadside radiation patterns are obtained and the variations of antenna gain are small for frequencies within the two resonant modes. Since the
Global Positioning System (GPS) has been launched, significant progress has been made in GPS receiver technology but the multipath error remains unsolved. As solutions based on signal processing are not adequate, the most effective approach to discriminate between direct and multipath waves is to specify new and more restrictive criteria in the design of the receiving antenna. An innovative low profile, lightweight dual band GPS radiator with a high multipath-rejection capability is presented by L. Boccia et al. The proposed solution has been realized by two stacked shorted annular elliptical patch antennas [66]. J. Anguera et al. proposed a triple-frequency antenna combining a dual-band and a single band antenna with broadside radiation patterns [67]. The dual-band antenna is inspired in the Sierpinski fractal. Such a dual-band antenna is stacked over a single band antenna. The antenna presents a broadband behavior at each band thanks to parasitic patches. The antenna has been designed using a MoM commercial code and has been experimentally tested, obtaining three bands with a broad bandwidth, high efficiency, and similar radiation patterns.

Yahya Rahmat-Samii developed a novel compact and light-weight dual-frequency, dual linearly polarized, high-efficiency, stacked-patch microstrip-array antenna for use in standalone aircraft-based remote sensing applications [68]. The sixteen-element stacked-patch array antenna optimized for center frequencies of 1.26 GHz and 1.413 GHz with 10 MHz and 25 MHz bandwidths in each band, respectively. Due to the large number of design parameters and demanding design requirements of beam-efficiency, side lobe levels, and polarization characteristics, particle-swarm optimization (PSO) and Finite-Difference Time-Domain (FDTD) simulations were used for synthesis and analysis. Cancellation techniques, based on symmetry, were applied to the antenna ports, with a custom-built feed network to reduce cross polarization.
Simulations and measurement results from a spherical near-field test facility confirmed excellent performance of the array configuration, with a beam efficiency of greater than 90%, isolation better than -35 dB, and cross polarization in the main beam of the array better than -40 dB.

Xiulong Bao et al. [69] used a single layer annular slot antenna to achieve dual-frequency and dual-sense circular-polarization by adjustment of the key antenna parameters, which are the inner and outer radii of annular-slot, the length of the four additional linear slots spurred from the annular slot and the length of microstrip feed line. The proposed antenna can provide broad impedance bandwidth and axial-ratio bandwidth. The right-hand circular polarization and left-hand circular polarization performance is realized simultaneously, for the first and second frequency, respectively. The proposed slot antenna can find useful application in indoor wireless communication systems and in satellite navigation systems.

2.3 Reconfigurable antennas

Reconfigurable antennas have become more attractive with the increased demand for multiband antennas. They provide more levels of functionality to a system by eliminating the need for complicated wideband antenna solutions. Common antenna designs not involving reconfigurability impose restrictions on the system performance because of their fixed structure. Reconfiguring antennas can enhance their performance by providing the ability to adapt to new operating scenarios.

There are several methods that rely on geometry reconfiguration for the tuning of the operating frequency of a particular antenna design, including varactor and PIN diodes, and the use of optically activated switches by fiber optic cables [70-73]. Many antennas have been designed to maintain their
radiation characteristics by using self-similar structures, while changing the aperture dimensions for a different operating frequency [71]. Other design consists of using a linear dipole antenna that is shortened to a specific length to operate at a higher frequency [72]. In the reconfigurable dipole case the radiation pattern stays the same because the antenna current distribution will be the same relative to the wavelength of the resonant frequency. Some reconfigurable antenna applications change the radiation pattern but maintain the same resonant frequency [73]. This concept can enhance a system’s ability to null jamming, or undesirable noise sources by directing the energy to the intended user.

The challenge faced by antenna designers is that the reconfiguration of one property, for example, frequency response, will have an impact on radiation characteristics. Likewise, reconfigurations that result in radiation pattern changes will also alter the antenna’s frequency response. This linkage is not desirable among antenna developers, which usually prefer the characteristics to be separable.

2.3.1 Reconfigurability Concept

The concept of reconfigurable antennas refers to a change in the frequency characteristics, radiation pattern, impedance bandwidth, and/or polarization of an antenna by changing its aperture dimensions or geometry through electrical or mechanical means. By tuning the operating frequency, the antenna could be used to filter signals interfering with the communication or simply to change operating frequency band [74].
2.3.2 Frequency Reconfigurability

Antennas with reconfigurable frequency response (also known as tunable antennas) can either switch abruptly from one frequency band to another or continuously perform this task. The frequency response reconfigurability is achieved by actively controlling the effective electrical length of the antenna thus enabling the antenna to operate in different frequency bands. This is usually done by adding or removing a part or parts of the antenna through electrical, mechanical, optical, or other means [71-76]. The antenna resonant frequency can also be altered by maintaining the antenna footprint but changing the radiating current path [77].

2.3.3 Radiation Pattern Reconfigurability

The radiation pattern reconfigurability is needed to steer the radiation pattern away from noise sources or to reduce interference. To reconfigure the radiation pattern, some researchers have used shorting pins and in-line open tuning elements [78]. Possible applications for this type of antennas are in phased antenna arrays in wide-angle scanning. There are methods to change radiation patterns independently from frequency behavior. One of these methods is the use of electrically tuned or switched parasitic elements. This method provides isolation of the driven element from the tuned element or elements, potentially wide frequency bandwidth, and a range of available topologies and functionalities [70]. This technique relies on the mutual coupling between closely spaced driven and parasitic elements, resulting in effective array behavior from a single feed point. Therefore, changes in radiation patterns are achieved through changes in the coupling between the elements, which, in turn, changes the effective source currents on both the driven and parasitic elements.


2.3.4 RF-MEMS Based Reconfigurable Antennas

The concept of reconfigurable RF MEMS based antenna systems was first introduced in 1998 by E. R. Brown [79] and many researchers have enthusiastically studied this area since then. In the past, the resonant frequency of the microstrip patch antenna was tuned by adjusting the effective length of the patch using varactor diodes [80]. RF MEMS switches have replaced FETs and diodes in certain applications. They have been fabricated, tested and measured against these solid state devices and were found to have few advantages for low and medium power handling applications [79, 81]. Nevertheless, the integration of RF MEMS switches hasn’t been demonstrated and/or explained in depth.

Anagnostou et al. demonstrated the concept of reconfigurable antenna design and fabrication with self-similar fractal antennas [82]. In their design, they started by characterizing a single antenna element and then improving their design and fabrication process for achieving a multiple-frequency antenna. These antennas have the advantage of radiating similar patterns in a variety of frequency bands. Their design, feed, and performance as well as the structure and the biasing network of the used RF-MEMS switches were the primary objective of the research. They also presented the functionality of a new type of RF-MEMS based reconfigurable multiband antenna consisting on a self-similar design, and introduced an analytical procedure to be used in their antenna design. Even though their antenna design had good characteristics, its performance showed relatively shallow resonances, with respect to a return loss $S_{11} = -10 \text{ dB}$, which they improved later.

The Sierpinski multiband fractal antenna was introduced in 1998 [75]. This antenna is described by an infinite number of iterations with an infinite
number of frequency bands resulting in a very complex antenna structure. Their approach was to apply low pass filters between the triangle interconnections to suppress any side-lobes that may exist after the first resonance. Most of the research regarding Sierpinski antennas has been done for a low relative permittivity structure etched on thin dielectric materials, thus approximating the free space environment. Anagnostou et al. also followed the principles of the Sierpinski antenna to design their own RF MEMS-based reconfigurable Sierpinski [76]. They implemented three sets of RF MEMS switches with different actuation voltages to sequentially activate and deactivate parts of a multiband Sierpinski fractal antenna. The direct actuation of the electrostatic MEMS switches was done through the RF feeding line. The antenna was fabricated over a liquid crystal polymer substrate and operates at several different frequencies between 2.4 and 18 GHz. It was the first RF MEMS reconfigurable antenna on a flexible organic polymer substrate for multiband antenna applications.

Gabriel M. Rebeiz studied the use of RF MEMS switches in microstrip patch antennas and feed structures for developing reconfigurable multiband antennas [81]. He named the design reconfigurable patch module (RPM). The RPM consists of a 3x3 array of patches connected together using MEMS switches. However, the real MEMS switches were not implemented since they were not available. Instead, they simulated the MEMS switches using ideal open and closed circuits. Their contribution is that they were able to achieve 12% impedance bandwidth for the L-band configuration and greater than 7% bandwidth at X-band, demonstrating that with the RPM the frequency was reconfigured from one band to another. Rebeiz also talks about the integration of RF MEMS switches as ideal elements for reconfigurable antennas in his
book [83]. He does a slight comparison of them against their solid state devices counterparts, FET switches and P-I-N diodes.

Jennifer T. Bernhard from University of Illinois at Urbana Champaign also performed much research on this field, implementing the concept of integrating packaged RF MEMS switches into a square spiral antenna by surface mounting techniques [84]. In their research, they modified the switch to reduce the impedance mismatch, as well as the antenna to physically and electrically accommodate the switch. An electrically active single stub matching network is included in their design, but only in one of the antenna configurations. Concurrent with this previous work, a research group from University of California at Irvine, supported by DARPA and NSF, presented a reconfigurable rectangular spiral antenna with a set of MEMS switches, which were monolithically integrated and packaged onto the same substrate [85]. This system was based on a single-arm rectangular spiral antenna, capable of changing its radiation pattern. C. W Jung et al. considered their design “the first truly reconfigurable printed antenna design using MEMS devices as active elements integrated in the same low loss substrate”. The effort of the proposed system was to emphasize the feasibility of MEMS switches integration into the same substrate for antenna applications.

Another interesting writing from a research group at Auburn University in Alabama deals with a MEMS-based electrostatically tunable circular microstrip patch antenna [86]. They designed a tunable circular microstrip patch antenna, fabricated by using printed circuit processing techniques. The microstrip patch antenna was patterned on the top side of a Kapton polyimide film, suspended above the ground plane. The patch was inductively coupled to a coplanar waveguide feed line via a slot in the ground plane. The only drawback to this work was that for a tuning range of 270 MHz, they needed an actuation
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Voltage of 165V. Previously, they were able to achieve a higher frequency range using 268V [87]. This is considered a high voltage since there are many products in the market with actuation voltages below 100 V and with similar characteristics [88]. Because the substrate used was not compatible for fabricating MEMS switches they needed to treat them as packaged lumped components, and use surface mounting techniques.

A novel design of a reconfigurable slot aperture antenna consists of interleaved crossed-slot elements for dual-polarized and broadband array operation without grating lobes [89]. The dimensions of the array elements can be reconfigured by using radiofrequency switches, such as RF-MEMS switches or P-I-N diodes. The array elements along with the switches are integrated into the top layer of a multilayered composite structure consisting of passive, resistively loaded frequency selective surface (FSS) elements that form a broadband ground plane system. The analysis of the FSS slot array configuration and measurements that could serve as a reference in future developments of the FSS layered arrays was emphasized. The private industry has also seen the need for the design of reconfigurable antennas in order to reduce the complexity of an antenna system for performance over a wide frequency band [90]. A work presented in 2001 describes a reflective antenna array approach that can perform time delay beam steering by using cascaded RF-MEMS switches/coplanar strip transmission line sections. They measured the RF-MEMS switches characteristics in coplanar strip transmission line and modeled a reflected phase of five cascaded switch transmission line sections. The true-time delay switched beams were created by placing the RF-MEMS switches along the transmission lines behind the flared notch elements, where RF-MEMS switches were proposed to be the reflective elements [91]. The switches were characterized as coplanar strip elements by designing test
substrates fabricated with switches placed in both shunt and series configurations, as they used coplanar strip transmission lines to eliminate the need for a balun to microstrip line.

The MEMS switches are being researched for better radiation performance for specific applications in antenna designs. A research group in University of California at Irvine designed an air bridged RF-MEMS capacitive series switches in single pole single throw (SPST) transmission lines for reconfigurable antenna applications [92]. In their design, they analyzed the RF characteristics of the capacitive series switches, measured, and compared with coplanar waveguide and microstrip line structures. They fabricated the series switches monolithically on a glass wafer with a spiral antenna that operates at 11 GHz in order to measure the radiation characteristics of the antenna. They concluded that the use of RF-MEMS series switch shows better performance for electric field radiation of reconfigurable antenna applications. Other researchers have designed integrated systems of antennas and MEMS on the same substrate as well [85]. The main difference between [76] and [93] is the substrate used. They have proved the feasibility of RF-MEMS-based reconfigurable antennas for many applications and the research to be done in order to fulfill future communication needs.

2.4 Simulation and Optimization

The use of simulation software is essential in order to achieve our goals. The software used should facilitate the calculation of the location of the antenna’s feed point, as well as the theoretical behavior of such structure. The simulation models of the investigated antennas are developed in Ansoft High Frequency Structure Simulator (HFSS). HFSS is a commercial Finite Element Method (FEM) solver for electromagnetic structures from Ansoft Corporation.
It is one of the most popular and powerful applications used for the complex RF electronic circuit elements and filters. 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, and 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 [94].

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 optimization tool available with HFSS is very useful for antenna engineers to optimize the antenna parameters very accurately. There are many kinds of boundary schemes and excitation techniques available in HFSS. Radiation boundary and PEC boundary are widely used in this work. The vector as well as scalar representation of E, H and J values of the device under simulation gives a good insight in to the problem under simulation.
2.5 Antenna fabrication

Printed antennas are usually fabricated on microwave substrate materials using standard photolithographic techniques or chemical etching methods. Selection of proper substrate material is the essential part in antenna design. The dielectric constant, loss tangent, homogeneity, isotropicity and dimensional strength of the substrate all are of importance. High loss tangent substrate adversely affects the efficiency of the antenna especially at high frequencies. The selection of dielectric constant of the substrate depends on the application of the antenna and the radiation characteristics specifications. High Dielectric constant substrates cause surface wave excitation and low bandwidth performance. After the proper selection of the substrate material a computer aided design of the geometry is initially made and a negative mask of the geometry to be generated is printed on a butter paper. A single side copper cladded substrate of suitable dimension is properly cleaned using acetone and dried in order to avoid the discontinuity caused by the impurities. 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 negative photo resist material is coated using spinning technique on copper surfaces and it is dried. The mask is placed onto the photo resist and exposed to UV light. After the proper UV exposure the layer of photo-resist material in the exposed portions hardens which is then immersed in developer solution for few minutes. The hardened portions will not be washed out by the developer. The board is then dipped in the dye solution in order to clearly view the hardened photo resist portions on the copper coating. After developing phase the unwanted copper portions are etched off using Ferric Chloride (FeCl₃) solution to get the required antenna geometry on the substrate. The etched board is rinsed in running water to remove any etchant. FeCl₃ dissolves the copper parts
except underneath the hardened photo resist layer after few minutes. The laminate is then cleaned carefully to remove the hardened photo resist using acetone solution. The various steps involved in the fabrication process is illustrated in figure 2.1

To implement frequency and polarization reconfigurable microstrip antennas, a few non-linear smd components need to be integrated into the surface of the fabricated antenna. For this a high precision soldering station with temperature control is used.

2.6 Excitation Technique

To excite the resonant modes with good matching, the matching point inside the patch can be easily achieved by a proximity coupling from a microstrip feed line, which is slightly displaced from the two principal axes of the patch. The width of the microstrip line is designed for 50 Ω characteristic impedance using HP AppCAD software. The optimum matching location can be easily determined by sliding the patch along the surface of the feed line. Since the characteristic impedance $Z_0$ is determined by the width of the microstrip line $W_f$ and the dielectric constant of the substrate over which the feed line is fabricated. The standard design equations are


Figure 2.1 Step by step procedure involved in photolithographic process

\[ Z_0 = \frac{Z}{2\pi \sqrt{\varepsilon_{\text{eff}}}} \ln \left( \frac{8h}{w_f} + \frac{w_f}{4h} \right) \Omega \text{ when } \frac{w_f}{h} \leq 1 \]

For \( \frac{w_f}{h} \geq 1 \),

\[ Z_0 = \frac{Z}{\sqrt{\varepsilon_{\text{eff}}}} \left( \frac{w_f}{h} + 1.393 + 0.667 \ln \left( \frac{w_f}{h} + 1.444 \right) \right) \Omega \]

Where \( Z \) is the characteristic impedance of free space and \( h \) is the substrate thickness. The substrate used for the fabrication of all antennas is FR-4 substrate of dielectric constant 4.4 with height 1.6mm. For this substrate, the width \( W_f \) of the feed line corresponding to characteristic impedance 50\( \Omega \) is found to be 3mm.

2.7 Antenna measurement facilities

A brief description of equipments and facilities used for the measurements of antenna characteristics is presented in this section with details of the measurement procedure.
2.7.1 HP 8510C Vector Network analyzer (VNA)

HP8510C is sophisticated equipment capable of making rapid and accurate measurements in frequency and time domain [95]. The network analyzer can measure the magnitude and phase of the S parameters. 32 bit microcontroller MC68000 based system can measure two port network parameters such as S11, S12, S22, S21 and it’s built in signal processor analyses the transmit and receive data and displays the results in many plot formats. The network analyzer consists of source, S parameter test set, signal processor and display unit. The synthesized sweep generator HP 83651B uses an open loop YIG tuned element 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 is connected to the two port S parameter test set unit, HP8514B and incident and reflected wave at the port are then down converted to an intermediate frequency of 20MHz and fed to the detector. These signals are suitably processed to display the magnitude and phase information in the required format. These constituent modules are interconnected through HPIB system bus. An in-house developed MATLAB based data acquisition system coordinates the measurements and saves the data in the text format. HP 8510C VNA is mainly used for the antenna radiation pattern measurements.

2.7.2 Agilent E8362B Precision Network Analyzer

The Agilent E8362B vector network analyzer is a member of the PNA Series network analyzer platform and provides the combination of speed and precision for the demanding needs of today's high frequency, high-performance component test requirements. The PNA Series meets these testing challenges by providing the right combination of fast sweep speeds, wide dynamic range, low trace noise and flexible connectivity. The operating frequency of the system is
from 10 MHz to 20 GHz. It has 16,001 points per channel with < 26 µsec/point measurement speed. This analyzer is used for the reflection coefficient studies and the measurement setup along with the specifications of the PNA is depicted in figure 2.2.

![PNA E8362B](image)

**Figure 2.2** Measurement setup and PNA Specifications

<table>
<thead>
<tr>
<th>Table 2.1 Specifications of PNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Band</td>
</tr>
<tr>
<td>IF Bandwidth</td>
</tr>
<tr>
<td>RF Connector</td>
</tr>
<tr>
<td>CPU</td>
</tr>
<tr>
<td>I/O ports</td>
</tr>
<tr>
<td>O/S</td>
</tr>
<tr>
<td>Measurement Automation Software</td>
</tr>
</tbody>
</table>

**2.7.3 Anechoic chamber**

The Anechoic chamber is an acoustic free room used to measure the antenna characteristics accurately. The room consists of microwave absorbers fixed on the walls, roof and floor to avoid EM reflections as shown in figure...
2.3. High quality low foam impregnated with dielectrically / magnetically lossy medium is used to make the microwave absorber. The tapered shapes of the absorber provide good impedance matching for the microwave power impinges upon it. Aluminium sheets are used to shield the chamber to avoid electromagnetic interference from surroundings.

2.7.4 Automated turntable assembly for far field measurement

The turn table assembly kept at distance greater than $\frac{2D^2}{\lambda}$ consists of a stepper motor driven rotating platform for mounting the Antenna under Test (AUT). An indigenously developed microcontroller based antenna positioner STIC 310C is used for radiation pattern measurement. The AUT is used as the receiver and a standard wideband ridged horn (1-18GHz) is used as transmitting antenna for radiation pattern measurements. The main lobe tracking for gain measurement and radiation pattern measurement is done using this setup. Antenna positioner is interfaced to the computer and with the in-house developed software ‘Crema Soft’ automatic measurements can be carried out.

*Figure 2.3* Photograph of the anechoic chamber used for the antenna measurements
2.7.5 Crema Soft: Automated antenna measurement

The user friendly software CremaSoft is built in MATLAB™ environment. The powerful instrument control toolbox of the package is used for communicating with the stepper motor control and Network Analyzer using the GPIB interface. This automated software can be used for calibration, antenna measurements and material characterization of the substrate used for the antenna design.

2.8 Measurement of Antenna characteristics

The antennas, in general, are characterized by parameters like input impedance, efficiency, gain, effective area, radiation pattern, and polarization properties [96]. The experimental procedures followed to determine the antenna characteristics are discussed in the following sections. Power is fed to the antenna from the S parameter test set of antenna through different cables and connectors. The connectors and cables will have its losses associated at higher microwave bands. Hence 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. Return loss, VSWR and input impedance can be characterized using single port calibration method.

2.8.1 Reflection coefficient and VSWR

The reflection coefficient (Γ) at the antenna input is the ratio of the reflected voltage (current) to the incident voltage (current) and is same as the $S_{11}$ when the antenna is connected at the port 1 of the network analyzer. It is a
measure of the impedance mismatch between the antenna and the source line. The degree of mismatch is usually described in terms of input VSWR or the return loss. The return loss (RL) is the ratio of the reflected power to the incident power, expressed in dB as

$$RL = -20\log(|\Gamma|) = -20\log(|S_{11}|) = -|S_{11}|(\text{dB})$$

The return loss characteristic of the antenna is obtained by connecting the antenna to any one of the network analyzer port and operating the VNA in S11/S22 mode. The calibration of the port is done for the frequency range of interest using the standard open, short and matched load. The calibrated instrument including the port cable is now connected to the device under test. The frequency vs reflection parameter (S11/S22) values is then stored on a computer using the ‘Crema Soft’ automation software.

The frequency corresponding to return loss 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. The antenna bandwidth is usually expressed as percentage of bandwidth, which is defined as

$$\%\text{Bandwidth} = \frac{\text{bandwidth}}{\text{centre frequency}} \times 100$$

The voltage standing wave ratio (V SWR) is the ratio of the voltage maximum to minimum of the standing wave existing on the antenna input terminals. A well-matched condition will have return loss of 15dB or more. A VSWR equal to 2 gives a return loss of $\approx 10$dB and it is set as the reasonable limits for a matched antenna.
2.8.2 Antenna Gain

Antenna gain is the ratio of the intensity of an antenna’s radiation in the direction of strongest to that of a reference antenna when both the antennas are fed by the same input power. If the reference antenna is an isotropic antenna, the gain is often expressed in units of dBi. The gain of the antenna is a passive phenomenon - power is not added by the antenna, but redistributed to provide more radiated power in certain directions than would be transmitted by an isotropic antenna.

The gain of the antenna under test is measured using the gain transfer method [96-97]. This method uses two standard wide band ridged horn antennas and the AUT. One of the antennas whose gain chart is available is chosen as the reference antenna ($G_{\text{ref}}$ (dBi)). The reference antenna is placed in the antenna positioner and boresighted. THRU calibration is made for the frequency range of interest. Standard antenna is then replaced by the AUT and the transmission coefficient $S_{21}$ (dB) is recorded. 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, provided by the manufacturer.

2.8.3 Radiation Pattern

The measurement set up is illustrated in figure 2.4. The radiation pattern of an antenna is graphical representation of its radiation properties as a function of the space coordinates. This assumes a three dimensional (3-D) pattern. Because of the limits set by the practical measurement setup for measuring the 3-D pattern, usually patterns are measured in the two principal coordinate planes (YZ and XZ) for antennas with omni-directional patterns. The far field
patterns are measured at a distance \( d > 2D^2/\lambda \), where \( D \) is the largest dimension of the antenna and \( \lambda \) is the smallest operating wavelength.

**Figure 2.4** Radiation Pattern Measurement Setup
The measurement of far field radiation pattern is conducted in an anechoic chamber or using the time gating facility of Vector Network Analyzer HP8510C to ensure a reflection free environment. 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 the remote computer.

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 is 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 radiations if any. The Crema Soft will automatically perform the radiation pattern measurement and store it as a text file.
References


94. HFSS User’s manual, version 10, Ansoft Corporation, July 2005
