PROPERTIES OF MULTIPLE MICROSTRIP ANTENNAS IN SEVERAL LAYERS OF ANISOTROPIC MATERIAL

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TABLE OF CONTENTS

ABSTRACT

Research for computing the input impedance and mutual coupling between microstrip antennas on multiple anisotropic layers is presented. The first chapter is a brief introduction of the microstrip antenna and the concept of mutual coupling. A history of the extensive amount of research dedicated to microstrip antennas is summarized. This will show that computing input impedance and mutual coupling on certain structures with multiple anisotropic layers and microstrip antennas has never been done before. The second chapter is a formal statement of the proposed research and a list of technical objectives that need to be met in order to answer the proposed questions. Finally, the third and fourth chapters include a discussion of anticipated results and conclusions.

CHAPTER 1. INTRODUCTION

1.1. Background

Since Deschamps's [1] formal presentation of a microstrip antenna in 1953 and detailed discussion by Alexopoulos [2] there has been an extensive amount of research devoted to the study of various printed antennas and arrays. It is well known that printed antennas are [3] very light, occupy a small volume, are useful at high frequencies and provide a wide range of patterns; thus making them very useful in many applications.

The following section defines and briefly discusses several properties of a microstrip antenna. Discussing these properties here will lay the foundation for the proposed research. We will start by describing the types of structures under investigation and illustrate the fields above and around the conducting surfaces. Then an expression for resonant length is given and the significance of this expression is discussed. After this the idea of mutual coupling is presented and illustrated with a two-port antenna network.

1.1.1. The microstrip antenna and mutual coupling

A microstrip device has two planar conducting layers separated by a thin dielectric material [4]. The top conducting layer is usually driven by a source and the lower conducting layer acts as a ground plane. The microstrip device in Figure 1 has a conducting patch separated from the ground plane by a material denoted as the dielectric substrate with thickness d. This type of microstrip device is called a microstrip patch antenna. Usually the length L of the conducting patch in Figure 1 is an appreciable fraction of the source wavelength. Because of this the microstrip patch antenna belongs to the class of resonant antennas [4]. The resonant nature of the antenna inherently results in a narrow bandwidth and very large dimensions at frequencies below 1GHz. Thus microstrip antennas are typically used at frequencies of 1GHZ to 100GHz [4].

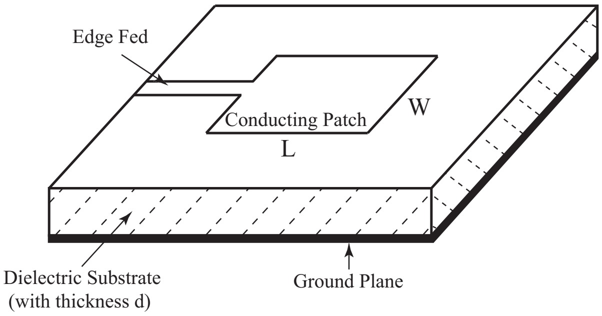

Figure 1. Microstrip antenna.

The region between the conducting patch and ground plane acts like the region between a transmission line and a ground plane with both ends open. This leads to a standing wave in the dielectric. The fields associated with the standing wave between the conducting patch and ground plane are shown in Figure 2. We can see that the fringing fields at each end of the conducting patch are 180^o out of phase and equal in magnitude. It is these fringing fields exposed to the region above the conducting patch that are responsible for the radiation.

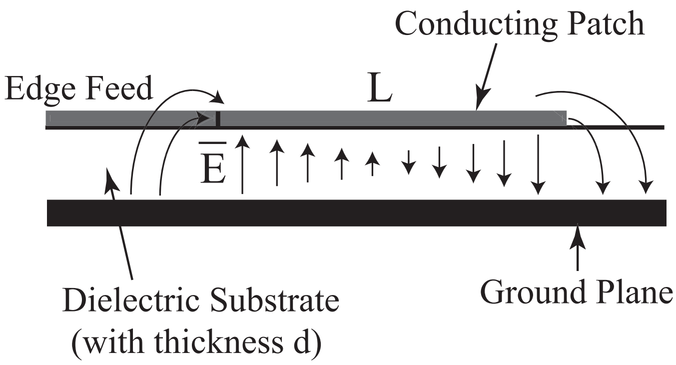

Figure 2. Side view of microstrip antenna.

The top view of the fields are shown in Figure 3. The arrows at each end of the conducting patch are illustrating the electric field component in the same plane of the conducting patch. We can see that the fields are in phase and lead to a broadside radiation pattern.

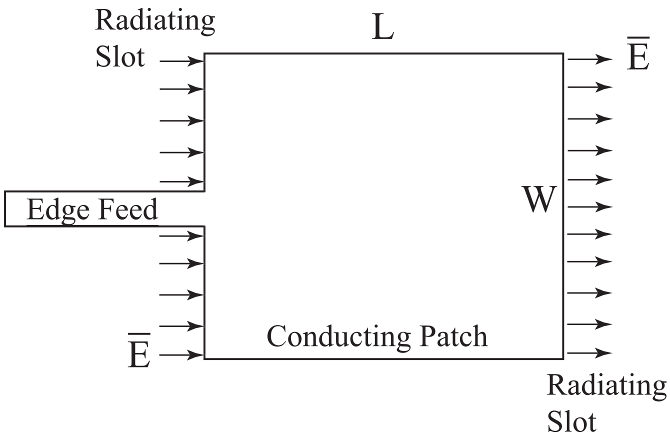

Figure 3. Top view of microstrip antenna.

We can also approximate the resonant length and input impedance at resonance for the antenna in Figure 1 which is edge fed with a microstrip transmission line. The length L and width W of the patch are chosen to give a real input impedance on and near the operating frequencies. Just like a dipole the resonant length L is approximately .5λ but the fringing fields in Figure 3 act to extend the effective length of the patch. Thus the patch length needs to be a bit shorter than a half-wavelength to achieve resonance. It has been shown that for a substrate thickness much less than the source wavelength the resonant length L is approximately [4]:

$$L \approx 0.49\lambda_d = 0.49\frac{\lambda}{\sqrt{\varepsilon_r}} \tag{1.1}$$

where ε_r is the permittivity of the dielectric substrate, λ is the free space wavelength and λ_d is the wavelength in the dielectric substrate. (1.1) clearly shows that the patch length cannot vary much otherwise an input reactance begins to appear at the feed location. Also, the input impedance at resonance can be approximated as [4]

$$Z_A = 90\frac{\varepsilon_r^2}{\varepsilon_r - 1}\left(\frac{L}{W}\right)^2 \Omega. \tag{1.2}$$

(1.1) and (1.2) assumes that the antenna in Figure 1 is not located near any source in the region or other conducting bodies otherwise the expressions are not valid.

When driving an isolated printed antenna with an ideal source the input impedance of the antenna is dependent on the voltage at the terminal and the current induced on the antenna by the source. When another conducting element is brought into the region where the antenna is radiating then this other conducting element can effect the current distribution on the radiating antenna. This effect on the current distribution is called mutual coupling. In an antenna array mutual coupling can be caused by other array elements, feed networks and nearby conducting objects (enclosure, mounts, etc.) [4]. In particular, the mutual impedance Z_{mn} between two terminal pairs of antennas m and n is the open circuit voltage (V_{oc}) at the m^{th} terminal divided by the current supplied by the n^{th} terminal. This then gives

$$Z_{mn} = \frac{V_m}{I_n}. \tag{1.3}$$

The result in (1.3) can be derived from a reciprocity point of view. Start with the sources in Figure 4. The sources $\bar{J}_a$ and $\bar{M}_a$ are in volume V_a and sources $\bar{J}_b$ and

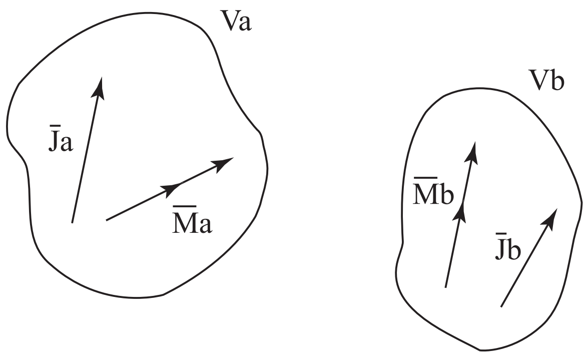

Figure 4. Radiating problem.

$\bar{M}_b$ are in volume V_b. Using the Lorentz reciprocity theorem [4] we denote the fields from $\bar{J}_a$ and $\bar{M}_a$ as $\bar{E}_a$ and $\bar{H}_a$, respectfully, and the fields from $\bar{J}_b$ and $\bar{M}_b$ as $\bar{E}_b$ and

$\bar{H}_b$, respectfully. If we assume that the frequency for all sources are the same then the Lorentz reciprocity theorem states that

$$\int\int_{V_a}\int (\bar{E}_b \cdot \bar{J}_a - \bar{H}_b \cdot \bar{M}_a)dv' = \int\int_{V_b}\int (\bar{E}_a \cdot \bar{J}_b - \bar{H}_a \cdot \bar{M}_b)dv'. \tag{1.4}$$

The left side of (1.4) is the reaction of the fields from sources b on sources a (measure of coupling) and the right side is the reaction of the fields from sources a on sources b. Now using the Lorentz reciprocity theorem we can derive the second reciprocity theorem. Suppose that sources a and b are antennas excited with an ideal current I_a and I_b, respectfully. This then implies $M_a = M_b = 0$. Thus,

$$\int\int_{V_a}\int \bar{E}_b \cdot \bar{J}_a dv' = \int\int_{V_b}\int \bar{E}_a \cdot \bar{J}_b dv'. \tag{1.5}$$

Now, the tangential component of the $\bar{E}$-field is zero on the surface of the antennas. Taking the current to be constant at the terminals then (1.5) reduces to the following line integral:

$$\int_{l_a} \bar{E}_b \cdot \bar{I}_a dl' = \int_{l_b} \bar{E}_a \cdot \bar{I}_b dl' \tag{1.6}$$

where $\bar{I}_a$ and $\bar{I}_b$ is the constant current at terminals a and b, respectfully. Then using $V = -\int \bar{E} \cdot d\bar{l}$, (1.6) becomes

$$V_a^{oc}\bar{I}_a = V_b^{oc}\bar{I}_b \tag{1.7}$$

where V_a^{oc} is the open circuit voltage of antenna a due to the field $\bar{E}_b$ generated by antenna b. Also V_b^{oc} is the open circuit voltage of antenna b due to the field $\bar{E}_a$ generated by antenna a. This then gives

$$\frac{V_a^{oc}}{\bar{I}_b} = \frac{V_b^{oc}}{\bar{I}_a} \tag{1.8}$$

which is the reciprocity theorem in circuit form. Using superposition we have $V_a = Z_{aa}\bar{I}_a + Z_{ab}\bar{I}_b$ and $V_b = Z_{ba}\bar{I}_a + Z_{bb}\bar{I}_b$ where Z_{ba} and Z_{ab} is the mutual impedance between antennas a and b and V_a, $\bar{I}_a$, V_b and $\bar{I}_b$ are the terminal voltages and currents on antenna a and b, respectfully [5]. If $\bar{I}_b = 0$ then $V_b = Z_{ba}\bar{I}_a$. This means that if antenna b is an open circuit then the open circuit voltage at antenna b due to the current driving antenna a is $Z_{ba}\bar{I}_a$. Solving for Z_{ba} gives $Z_{ba} = \frac{V_b}{\bar{I}_a}$. Similarly for $\bar{I}_a = 0$ we have $Z_{ab} = \frac{V_a}{\bar{I}_b}$.

Now, consider the two antennas in Figure 5. If an ideal current source $\bar{I}$ excites antenna a then $V_b = \bar{I}Z_{ba}$ where $\bar{I}_b = 0$. Now, if the same current $\bar{I}$ excites antenna b then $V_a = \bar{I}Z_{ab}$ where $\bar{I}_a = 0$. But $Z_{ab} = Z_{ba}$ implying $V_a = V_b = V$. Thus $\bar{I}$ will generate the same terminal voltage regardless of the terminal it is exciting. Reciprocity states that the source and measurer can be interchanged without changing the system response.

Figure 5. Two port antenna problem.

The above discussion introduces the concept of mutual coupling and how to calculate mutual impedances Z_{ab} and Z_{ba}. The antenna system in Figure 5 can take on many different forms. One of the forms that it can take on is that of multiple anisotropic layers with multiple microstrip antennas which is the work being proposed in this document. It is this idea of calculating mutual coupling between conducting elements that lead to the work in the following section.

1.1.2. Previous work on a microstrip antenna

Some of the initial work on microstrip antennas was in 1974 by Munson [6]. This work focused on microstrip antennas conformed to cylindrical antennas. Part of this work was based on work in 1969 by Campbell [7] which discussed omnidirectional antenna arrays. A year later, work by Howell [8] presented design guidelines for a large class of coaxial and edge fed microstrip antennas. This work included both linearly and circularly polarized antennas and treated the antenna as a radiating resonator.

In 1979 a significant step was taken by Uzunoglu, Alexopoulos and Fikioris which for the first time analyzed the radiaton properties of the microstrip dipoles [9] shown in Figure 6. This work is based on obtaining the Green's function for a horizontal Hertzian dipole printed on a grounded isotropic dielectric substrate. Working from that base, Rana and Alexopoulos presented work in 1981 on the current distribution and input impedance of printed dipoles [10]. The above work with Green's functions in the spectral form laid the foundation for future work by Pozar [11] and others to analyze properties of other various microstrip antennas.

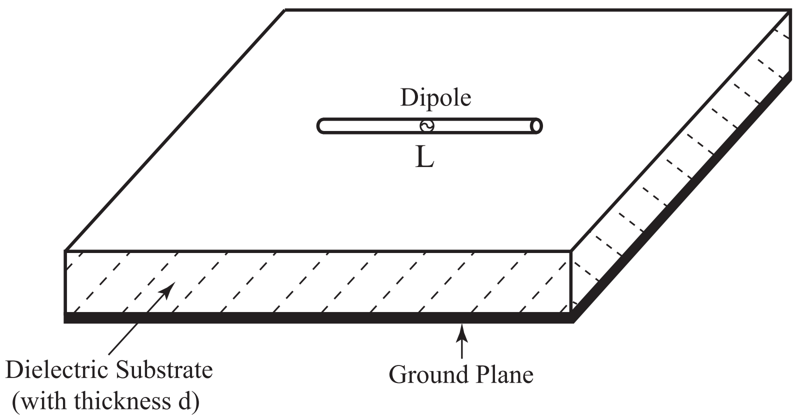

Figure 6. Printed dipole.

In parallel with the development by Alexopoulos and his colleagues, in 1980 and 1981, Itoh and Menzel [12]-[13] developed a spectral domain immittance approach to study microstrip antennas similar to the one shown in Figure 1. This method is based on an equivalent circuit concept for dispersion characteristics of printed transmission lines. This work included a spectral domain version of the Green's function and was applied to problems similar to the one shown in Figure 7 with multiple isotropic dielectric layers surrounded by a shield while the top and bottom dielectric layer was air. The spectral domain immittance approach used a full-wave analysis technique to overcome previous quasi-static analysis techniques of microstrip structures. This allowed structures comparable to the source wavelength to be analyzed. Then in 1982 Bahl, Bhartia and Stuchly [14] presented work on the design of microstrip antennas covered with an isotropic dielectric layer. The resonant frequency, loss and bandwidth of various antennas were studied by using a variational technique.

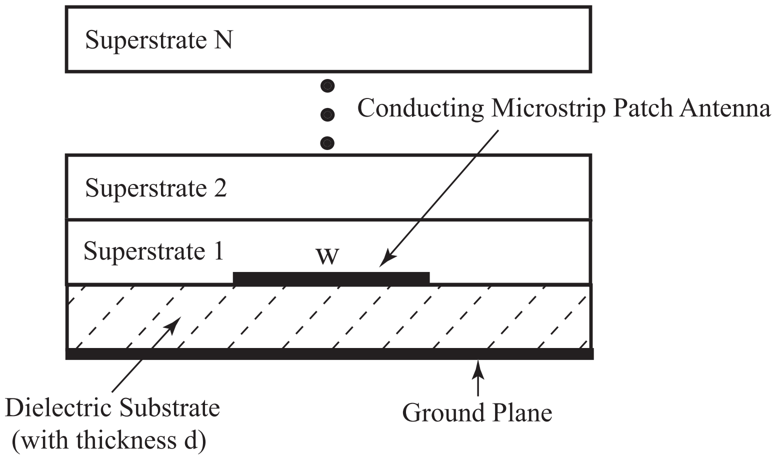

Figure 7. Layered microstrip antenna.

In 1982, Lee and Tripathi [15] extended the work by Itoh and Menzel and others to include microstrip structures with a planar anisotropic uniaxial substrates. This work was based on the Hertz Vector Potential Function and not on the equivalent circuit concept by Itoh and Menzel [13]. It was later shown by Nelson [16] that the immittance functions in both the methods presented by Lee and Tripathi and Itoh and Menzel where the same up to a negative sign. Then in 1984 Krowne [17] derived the spectral domain Green's function solution of an anisotropic layered structure in terms of Maxwell's equations. The anisotropic material could be biaxial or uniaxial. Later in 1986 Krowne [18] applies this technique to radiators and resonators in layered anisotropic structures. In 1987, Pozar [19] presented the radiation and scattering properties of a microstrip patch antenna on a uniaxial substrate. Pozar's results were developed using the spectral domain version of the Green's function found in previous work by Alexopoulos. Then in 1990 Nelson, Rogers and d'Assuncao [16] extended the problem in Figure 7 and investigated the effects of multiple anisotropic uniaxial dielectric layers on the resonant frequency of a rectangular microstrip antenna. This work used the full-wave immittance matrix technique. This lead to the results presented in 1996 by Oliveira and d'Assuncao [20] which investigated for the first time the input impedance of microstrip patch antennas on multiple anisotropic dielectric substrates.

The work mentioned above is just a summary of work over the past 33 years that has focused on the input impedance, efficiency, gain and patterns of printed antennas in layered anisotropic and isotropic structures. Although the summary presented is not about the idea of mutual coupling the summary is very important because the foundations for calculating mutual coupling is found throughout the work. Many other areas that involve different feed techniques, patch configurations, frequency selective structures and arrays exist and are not discussed here.

1.1.3. Previous work on mutual coupling

The computation of mutual impedance between antennas is an extensive topic. Some of the initial computations between printed dipoles was first done by Baker and LaGrone [21] in 1962 and then later by Alexopoulos and Rana [22] in 1981. The work by Baker and LaGrone assumed a current distribution with a dielectric substrate permittivity of one. Alexopoulos and Rana relax the current distribution assumption and use the Green's function in spectral form in terms of the Sommerfeld type integrals

[23] to solve for the mutual impedance between two printed dipoles over a grounded isotropic dielectric substrate. The printed dipoles are shown in Figure 8 with a specific separation. Alexopoulos and Rana present the mutual impedance for two dipoles in a broadside, collinear and echelon form. The significance of this work is that it shows for the first time that a spectral domain method can be used to compute mutual impedance between two printed antennas on a grounded dielectric substrate. Also in

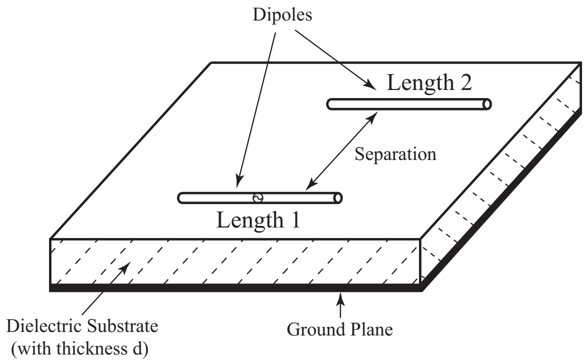

Figure 8. Printed dipoles.

1981 Jedlicka, Poe and Carver [24] present a method for measuring coupling between microstrip antennas. This method is shown in Figure 9 and involves attaching the ground plane of the two elements to a large rigid aluminum ground plane. Then spacers are inserted between the two antennas to act as a continuous dielectric substrate between the two antennas under test. As the antenna spacing increases dielectric spacers are inserted. The antennas are then driven by a network analyzer with a coax through the aluminum ground plane and it is shown that this provides good measurements of the transmission coefficient S_{12} between the two antennas. This work is also very significant in the area of studying mutual coupling because it shows a reliable, accurate and easy to build test setup. This will be very useful for validating the numerical techniques used to compute mutual coupling between various antennas in the research presented here.

The next step in the area of research involving mutual coupling was taken in

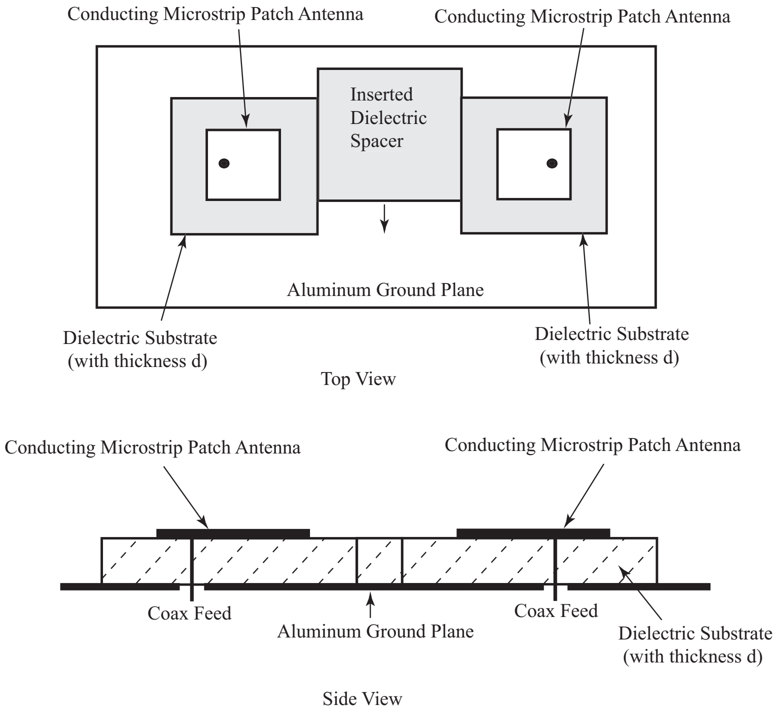

Figure 9. Test setup for measuring mutual impedance.

1982 by Pozar [11]. Pozar investigates the input impedance and mutual coupling between rectangular microstrip antennas. This is done by evaluating the exact Green's function for an isotropic grounded dielectric substrate with the moment method; thus accounting for surface waves and coupling to nearby antennas. Pozar then presents numerical and measured results for the input impedance and mutual coupling of various rectangular microstrip antenna configurations. Then in 1983 Newman, Richmond and Kwan [25] directly solve for the mutual impedance between two rectangular microstrip antennas similar to the structures in Pozar's work [11]. This was done by using the moment method to directly solve the reaction integral equation

$$-\int_S\int \bar{J}_s \cdot \bar{E}_T ds = \int_L \bar{J}_i \cdot \bar{E}_T dl \tag{1.9}$$

where the surface integral is over the surface of the conducting patches, the line integral is over the length of the electric field in the presence of the dielectric slab and

J_T is an arbitrary test current on the surface S. (1.9) can then be solved directly for J_S.

In 1984 a transmission line model for mutual coupling between microstrip antennas was presented by Lil and Capelle [26]. This model is presented assuming that the surface waves can be neglected and each rectangular resonator is approximated by two equivalent radiating slots. Again, in this case the author assumes that conducting patches are on the same isotropic grounded dielectric substrate. Then, in 1986, Hansen and Patzold present the input and mutual coupling of a rectangular microstrip antenna with a dielectric superstrate for the first time [27]. This was developed in the spectral domain from Richmond's reaction theorem. The dielectric substrates and superstrates were assumed to be isotropic and the conducting patches are on the same dielectric substrate. The input impedance and mutual coupling is presented for various conducting patch configurations.

In 1989 two papers were presented on the mutual coupling between elements in microstrip antenna arrays. First, a paper by Katehi [28] computed the mutual coupling between microstrip dipoles in multielement arrays. The dipoles were excited by an electromagnetically coupled transmission line in the isotropic substrates below the printed dipoles. The mutual impedance between various array configurations was then calculated using the dyadic Green's function. The second paper that appeared in 1989 was by Mohammadian, Martin and Griffin [29]. This work was on a theoretical and experimental study of mutual coupling in microstrip arrays. This was done by replacing each element of the array by an equivalent magnetic current source and using the reaction theorem to calculate the mutual impedance between two printed antennas on a grounded isotropic dielectric substrate. S_{12} is presented for both the E and H planes.

The 90's saw a lot of work on mutual coupling between antennas. During this time many other problems were looked at and, naturally, this work was based on the work from the 80's. In 1990 Benalla and Gupta [30] looked at the mutual coupling between rectangular microstrip antennas with an isotropic substrate and superstrate. In this work the antennas were edge fed and on the same dielectric layer. The mutual coupling was calculated by replacing the edge aperture field by an equivalent magnetic line source. The H-plane coupling is presented with respect to the antenna spacing. Numerical and theoretical results show good agreement. In 1991 Terret, Assailly, Mahdjoubi and Edimo [31] present a paper on mutual coupling on stacked microstrip antennas. They use the reciprocity theorem and the spectral domain Green's function used by Pozar [11]. The mutual impedance is then calculated using

$$Z_{21}^{p} = \frac{-\int_{V_2} \bar{E}^{(1)T} \cdot \bar{J}_{V_2}}{|I_{V_1}| \cdot |I_{V_2}|} \tag{1.10}$$

where Z_{21}^{p} is the transfer impedance between ports 1 and 2, $\bar{E}^{(1)T}$ is the total electric field at port 2 from the current at port 1, $\bar{J}_{V_i}$ is the current density at port i and I_{V_i} is the terminal current at the port i. In 1992 Pan and Wolff present work on computing the mutual coupling between slot-coupled microstrip patches in a finite array. This was done by using the spectral domain Green's function for an isotropic dielectric substrate. In this case the excitation source for each patch was taken into account by defining an equivalent N-port network. This allows the coupling mechanism to be modeled in the mutual coupling computations. The next step in mutual coupling computations between rectangular patch antennas was taken by Wahid and Voor [32]. In this case the microstrip patches were on the same isotropic dielectric substrate except this time the patches were skewed. This means that the H and E planes are not parallel. These computations are done by solving the exact Green's function [33]. Theoretical and measurement results compare well. Then, in 1995, Tam, Lai and Luk present work on mutual coupling between rectangular microstrip antennas on a cylindrical surface. With this work the authors studied the effect of curvature and separation on the mutual coupling between the printed antennas. The spectral domain Green's function was used to compute the mutual coupling and good comparison with measurements was shown.

It should be noted that all the work mentioned above was solved using the method of moments. At this point the work by Terret, Assailly, Mahdjoubi and Edimo [31] is the closest to the work presented here. This seems to be the first time mutual coupling is considered between two printed antennas on different isotropic layers.

1.2. Current work on microstrip antennas and arrays

More recently, printed antennas on multiple anisotropic materials have been revisited. In 2001, Verma and Nasimuddin [34] investigated the input impedance of rectangular microstrip antennas on multiple anisotropic layers. In this work it was assumed that the entire problem was above a ground plane and the top most anisotropic superstrate was capped by a conducting shield which differs from the work by Oliveira and d'Assuncao [20]. In 2003 Costa, Bianchi, Lacava and Cividanes [35] investigated the input impedance of an electromagnetically coupled microstrip antenna in multiple anisotropic layers. This was done by using a full-wave spectral domain technique and solved using the method of moments. Also, recently printed antennas have been developed [36]-[40] to provide a small surface area and wide-band characteristics. In 1998 Waterhouse, Targonski and Kokotoff [36] discuss the design and performance of using shorting posts on a microstrip patch antenna on an isotropic substrate. We can see in Figure 10 that a shorting post is a conducting material connected between the conducting patch and ground plane. By using shorting posts a smaller patch area and a higher bandwidth was achieved. Waterhouse, Targonski and Kokotoff show the predicted and measured input impedance and far-field patterns for an antenna similar to the one in Figure 10. Later in 2002, Li, Tsai, Tentzeris and Laskar [40] presented an antenna similar to Waterhouse, Targonski and Kokotoff for communication systems such as Bluetooth ISM. In 2001 Shackelford, Lee, Chatterjee, Guo, Luk and Chair [39] presented the small-sized wide-band U-slot and L-probe fed microstrip antenna with shorting walls shown in Figure 11. We can see that the printed antenna is on two isotropic layers. The printed antenna is on the second isotropic layer and the L-probe is on the first isotropic layer. Depending on the configuration a bandwidth (BW) of 45.1 percent is achieved. Later in 2004 two other broadband patch antennas were presented. Li, Chair, Luk and Lee [38] presented a triangular patch antenna with a folded shorting wall and air as the dielectric substrate. They presented the patterns, reflection coefficient S_{11} and show that the antenna has a BW of 36.2 percent. Chiu, Chan and Luk [37] also presented a broadband antenna with double shorting walls and air as the dielectric substrate. They presented the VSWR from 3.5GHz to 9.5GHz and observed a BW of 71.7 percent. This antenna is very useful for wide-band communications.

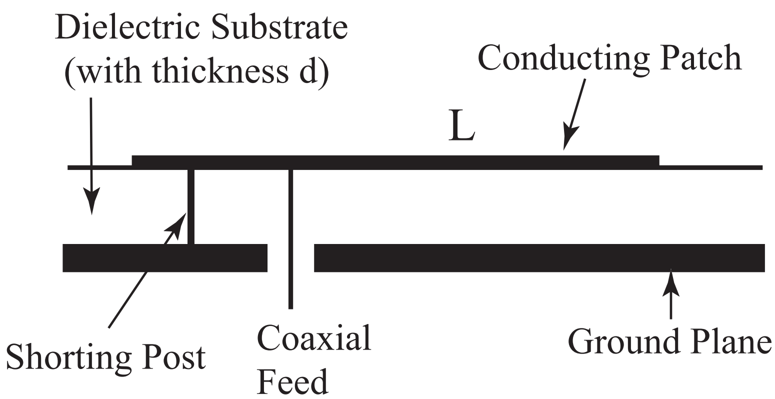

Figure 10. Microstrip antenna with a shorting post.

Dual band capabilities is another emerging field in antenna research. In 2006, Sheta, Boghdady, Mohra and Mahmoud [41] presented a dual-band microstrip antenna. They showed that by designing two antennas for different center frequencies

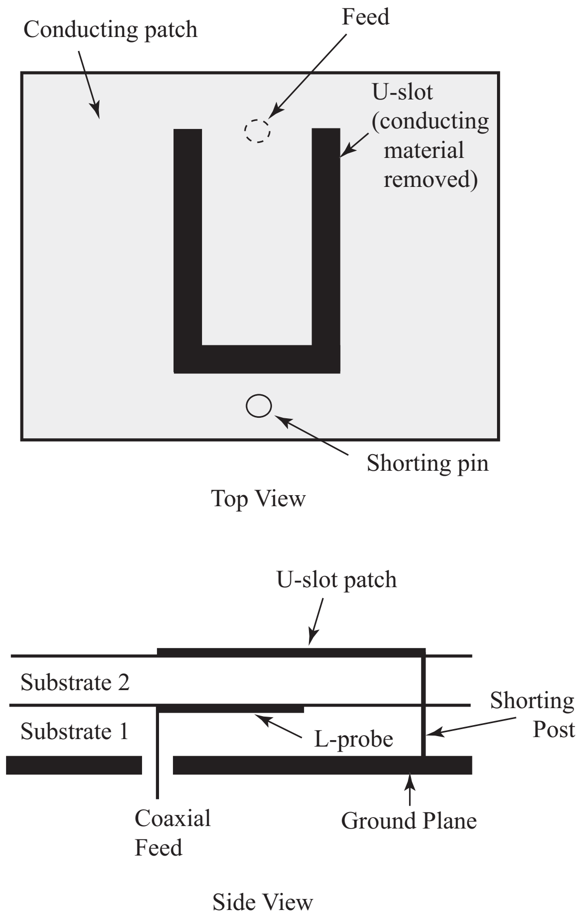

Figure 11. U-slot microstrip antenna.

and combining them appropriately the resulting antenna can operate near or at the two original center frequencies. They presented S_{11} and various far-field radiation patterns.

New properties on metamaterials [42]-[47] has also grown tremendously in the past several years. In 2003, Balmain, Luttgen and Kremer [47] presented a type of metamaterial that can be used as a superstrate to direct the field of a single antenna in a conical form through the material. These conical regions are called resonance cones. The authors show that the fields calculated by the moment method code are in good agreement with measurements. In 2005, Baccaralli and co-authors [43] investigate the modal properties of surface waves of grounded metamaterial for planar antennas. Preliminary results for the far-field patterns of a dipole source above grounded metamaterial was presented. Finally, in 2007, Jarkley and Eleftheriades [42] presented a negative-refractive-index metamaterial for incident plane waves of an arbitrary polarization. This was achieved by metalization patterns above and below an isotropic dielectric slab.

Significant research on mutual coupling has also been performed in the past few years. In 2003 Yang and Samii [48] presented a low mutual coupling design of an array of electromagnetic band gap structures. This structure was analyzed using the finite difference time domain (FDTD) method and used printed antennas on a single isotropic dielectric substrate. In 2005 Chair, Kishk and Lee [49] presented work on the mutual coupling between a 2 element array of circular patch antennas on an isotropic dielectric substrate. The computations were performed using the commercially available software IE3D [44] and S_{11} was shown versus frequency for various patch configurations. Then, in 2007, Buell, Mosallaei and Sarabandi [45] used metamaterial to suppress the mutual coupling between elements in a densely packed array. This was achieved by using metamaterial as isolation walls between the elements.

In this section we can see that significant research is still being conducted on microstrip antennas and arrays. But throughout this summary we can also see that the case of computing mutual coupling between microstrip antennas on multiple anisotropic layers has not been studied.

CHAPTER 2. PROPOSED RESEARCH

Chapter 1 has illustrated that the study of microstrip antennas and arrays has many areas of research. The information presented is only a brief summary of all the work conducted in the past four decades. But we can see that there is much more room for significant research to be conducted. The next several sections of this chapter clearly state the research questions being proposed and provide a plan for moving forward.

2.1. Properties of interest and research questions

When we study microstrip antennas we can see that there are many properties of interest. These include input impedance, resonant frequency, resonant dimensions, bandwidth, gain, efficiency, far-field patterns, near-field patterns and different feed techniques. If the antenna is in the presence of another conductor then in addition to all the properties just mentioned, mutual impedance and the transmission coefficient S_{12} are also of interest. From the summary on Chapter 1 we can see that more recent research involves printed antennas in complex structures such as layered anisotropic material [34], metamaterial [43] and structures with complex shorting walls [37]. But throughout all this research many fundamental questions have not been answered about the interaction between conducting elements in these types of environments. The research proposed here will attempt to answer several of those questions.

To introduce the proposed research we first consider the generalized layered structure in Figure 12. Each layer of material is a uniaxial anisotropic dielectric layer with each layer having an $\bar{\varepsilon}_r$ of

$$\bar{\varepsilon}_r = \begin{bmatrix} \varepsilon_2 & 0 & 0 \\ 0 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_2 \end{bmatrix}, \tag{2.1}$$

$\mu_r = \mu_0$ and $\sigma = 0$. Each layer can have a microstrip antenna defined on it except below layer 0 because of the ground plane. This structure will allow any number of conducting patches to be driven and any number to be parasitic elements. Note that the conducting patches can be printed dipoles, rectangular microstrip patches, circular patches, broadband triangular patches with shorting posts or any array configuration.

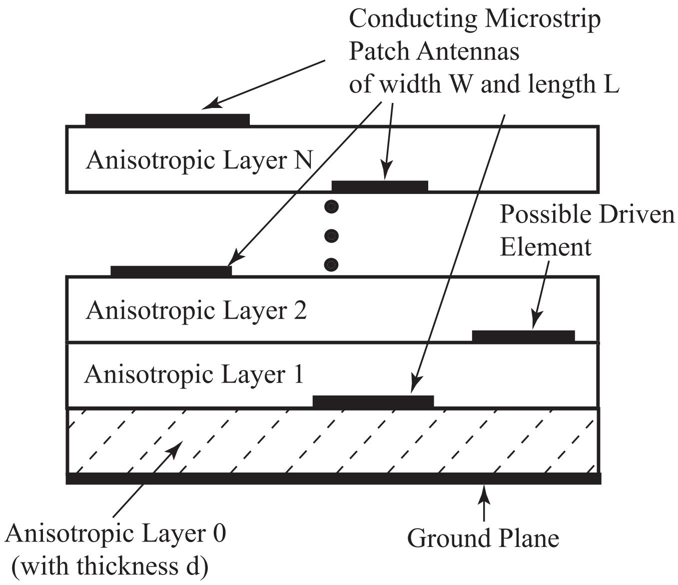

Figure 12. Layered microstrip antenna.

We can see that if any element is driven in the structure other printed conductors will have a significant impact on the properties listed above. At this point the work by Nelson, Rogers and d'Assuncao [16] has studied the resonant frequency of an isolated rectangular microstrip antenna in a structure similar to the one defined in Figure 12 and work by Oliveira and d'Assuncao [20] has presented the input impedance of an isolated rectangular microstrip patch above layer 0 and with two anisotropic superstrates. Thus, at this point, a number of other properties such as bandwidth, gain, efficiency, field patterns and feed techniques could be investigated. But with the presence of other conducting patches and other anisotropic layers the input impedance and mutual impedance may be of interest.

Thus the proposed research will consist of numerical techniques and measurements of a problem defined on the arbitrary structure in Figure 12 used to address the following two questions:

- What is the input impedance of a driven element in the layered anisotropic structure in the presence of other conducting patches defined on arbitrary anisotropic layers in the same structure?

and

- What is the mutual impedance between a driven element in the layered anisotropic structure and other conducting patches defined on arbitrary anisotropic layers in the same structure?

The previous two questions are very significant in many fields. One very large area is microstrip antenna arrays [3], [50]-[52]. Understanding the effect of mutual coupling between elements of an array and the feed can have a significant impact on the design and ultimately the performance. Another area of interest is the study of frequency selective structures [53]-[55]. Some of these structures contain many printed conductors and mutual coupling is present. Radio Frequency Identification (RFID) [56]-[61] is another very fast growing area. The application of many different UHF RFID tags in close proximity is an environment of extensive mutual coupling. A generalized version of the proposed research could study this effect on power harvesting capabilities and read ranges.

To answer these questions several items about the structure in Figure 12 must be defined. First, the types and significance of conducting patches and feed techniques for the driven element need to be defined. Second, the numerical technique and measurement method for validating the problem needs to be chosen. The following sections on technical objectives and work plan will outline the needed definitions.

2.2. Technical objectives

1. Choose the appropriate types of microstrip antennas that will allow the work to proceed to answer the proposed questions.

2. Choose and develop the numerical technique that can be used to compute the input impedance and mutual coupling between elements in the anisotropic structure.

3. Validate numerical results for the isotropic case with commercially available software.

4. Design and build a multiple layered structure to measure and validate the numerical calculations of input impedance and mutual coupling.

2.3. Work plan

Technical Objective 1: Choose the appropriate types of microstrip antennas that will allow the work to proceed to answering the proposed questions.

Three different types of antennas will be used for this research. The first one will be a set of printed dipoles similar to the ones used in the research by Alexopoulos and Rana in [10],[22]. We will start by reproducing the input impedance calculations in [10] and mutual coupling computations in [22]. This will be a significant step in verifying that the derivation of the numerical technique is valid and the usually extensive code making the calculations is also correct for isotropic material. The second problem will consist of a set of rectangular microstrip patches. This is chosen because the next step in validating the numerical technique can be taken by reproducing the results for anisotropic structures by Nelson [16], Oliveira [20] and Pozar [19]. By reproducing the work of Nelson and Oliveira it will be illustrated that structures with multiple anisotropic material can be analyzed with the newly developed code. Then, by reproducing the work of Pozar we will illustrate that the input impedance and mutual coupling between rectangular microstrip patches can be evaluated with our numerical technique. Once we know that the code is valid for rectangular microstrip antennas on a single or multiple anisotropic layer a new step can be taken by allowing printed conductors to be on arbitrary anisotropic layers. Although the previous work is novel, a third problem will be evaluated. This will include an ultra wide-band (UWB) antenna. At this point very little work exists on evaluating the input impedance and mutual coupling of a driven UWB antenna in the presence of other conducting bodies. In fact the evaluation of an isolated UWB antenna on layered anisotropic material appears to be novel and looking at the input impedance and mutual coupling between UWB antennas has a growing interest in the field of microstrip antenna arrays.

Technical Objective 2: Choose and develop the numerical technique that will compute the input impedance and mutual coupling between elements in the anisotropic structure.

At this point several different techniques can be used to answer the previous questions. This section will comment on three of the most common.

1) *Exact green's function for a grounded dielectric slab*

a) *Introduction*

Pozar presents a moment method solution for rectangular microstrip antennas that can calculate input impedance and mutual coupling between elements [11]. The method uses an exact Green's function for a grounded dielectric slab. Use of this accounts for surface waves and coupling with nearby conducting surfaces. To calculate the elements of the impedance matrix and voltage matrix in the moment method we start with a horizontal electric current element. To give an idea of how the method works, suppose that a grounded isotropic dielectric slab is centered in the x-y plane and we define a current element Il on the top of this dielectric slab with current flowing in the x-direction. For this case, the magnetic vector potential can be written as [11]

$$\bar{A}_x = \frac{\mu Il}{4\pi^2} \int \int_{-\infty}^{\infty} zG_1 e^{jk_x(x-x_0)+jk_y(y-y_0)} dk_x dk_y, \tag{2.2}$$

$$\bar{A}_y = 0, \tag{2.3}$$

$$\bar{A}_z = \frac{\mu Il}{4\pi^2} \int \int_{-\infty}^{\infty} k_x G_2 e^{jk_x(x-x_0)+jk_y(y-y_0)} dk_x dk_y \tag{2.4}$$

where zG_1, G_2, T_e, T_m are defined in [11]. The field point is at (x,y,z), the source location is at (x_0,y_0,d) and d is the dielectric thickness. Once $\bar{A}$ is determined the electric fields for this case are given by

$$\bar{E} = \frac{-j\omega}{\varepsilon_r k_0^2}(\varepsilon_r k_0^2 \bar{A} + \nabla\nabla \cdot \bar{A}). \tag{2.5}$$

The moment method is then employed to determine induced currents in all surfaces in the structure. Once the surface currents have been determined the input impedance can be determined. In addition, if the antenna is in the presence of another antenna the mutual impedance can be evaluated.

b) *Advantages/Disadvantages*

The numerical evaluation of (2.5) is quite extensive and difficult. This is due to the numerical integration from $-\infty$ to ∞ and the derivatives associated with $\nabla\nabla \cdot \bar{A}$. Although (2.5) was originally developed for patches on single isotropic layers, this method was later extended by Pozar [19] to include anisotropic materials and by Wang [62] in 2002 to multiple layers of anisotropic layers, as such, it could be used for our purposes. It should be noted that the fundamental questions proposed above were not addressed by Wang.

2) *Equivalent magnetic source*

a) *Introduction*

Another method for calculating mutual impedance is used by replacing the edge aperature field by an equivalent magnetic line source over a ground plane [30]. This magnetic line source may or may not have a dielectric superstrate. Thus if we have two elements, then we need to calculate the mutual coupling between two magnetic sources. It is shown in [30] that the mutual coupling admittance between two current elements i and j can be expressed as $Y_{ij} = \bar{J}_j W_j / V_i$ where W_j is the width of the jth element and V_i is the voltage of the ith element. The induced current density is written as [30]

$$\bar{J}_j = -\bar{H}^i_\rho \cos(\phi - \psi^j) - \bar{H}^i_\phi \sin(\phi - \psi^i) \tag{2.6}$$

where $\bar{H}^i_\rho$ and $\bar{H}^i_\phi$ are the magnetic field components defined in [30].

b) *Advantages/Disadvantages*

The expressions for $\bar{H}^i_\rho$ and $\bar{H}^i_\phi$ are much simpler than (2.5) because the integration is a single integration from 0 to ∞ and $\nabla\nabla\cdot$ is not involved. Thus making this method a good candidate for computing mutual impedance between elements. But further work would need to be done to determine if this could also solve for input impedance of a printed antenna on multiple anisotropic layers.

3) *Spectral domain immittance method*

a) *Introduction*

The spectral domain immittance method can be used to calculate the resonant length [16] and input impedance of microstrip antennas on multiple anisotropic materials [20]. In this method the electric and magnetic field in each layer is written in terms of the Hertz electric vector potential $\bar{\Pi}_e$ and magnetic potential $\bar{\Pi}_h$ in the following manner [16]:

$$\bar{H} = j\omega\varepsilon_0(\nabla \times \bar{\Pi}_e) \tag{2.7}$$

and

$$\bar{E} = -j\omega\mu_0(\nabla \times \bar{\Pi}_h). \tag{2.8}$$

Then substituting (2.7) and (2.8) into Maxwell's equation $\nabla \times \bar{E} = -j\omega\mu_0\bar{H}$ gives

$$\nabla \times \bar{E} = \omega^2\mu_0\varepsilon_0(\nabla \times \bar{\Pi}_e) \tag{2.9}$$

and

$$\nabla \times \nabla \times \bar{\Pi}_h = \bar{H}. \tag{2.10}$$

By using that the curl of a gradient is zero, the identity $\nabla \times \nabla\bar{\Pi}_h = \nabla(\nabla \cdot \bar{\Pi}_h) - \nabla^2\bar{\Pi}_h$ and extensive manipulation the following equations in terms of the Hertzian potentials can be written [16]:

$$\bar{H} = j\omega\varepsilon_0(\nabla \times \bar{\Pi}_e), \tag{2.11}$$

$$\bar{E} = \omega^2\mu_0\varepsilon_0\bar{\Pi}_e + \frac{1}{\varepsilon_e}\nabla(\nabla \cdot \bar{\Pi}_e), \tag{2.12}$$

$$\nabla^2\bar{\Pi}_e + \omega^2\mu_0\varepsilon_0\varepsilon_r\bar{\Pi}_e = 0, \tag{2.13}$$

$$\bar{E} = j\omega\mu_0(\nabla \times \bar{\Pi}_h), \tag{2.14}$$

$$\bar{H} = \nabla(\nabla \cdot \bar{\Pi}_h) - \nabla^2\bar{\Pi}_h \tag{2.15}$$

and

$$\nabla^2\bar{\Pi}_h + \omega^2\mu_0\varepsilon_0\varepsilon_r\bar{\Pi}_h = 0. \tag{2.16}$$

Then (2.13) and (2.16) are transformed into the Fourier domain. In this domain (2.13) and (2.16) take on the form of the wave equation, which has an algebraic solution. This then gives expressions for $\bar{\Pi}_e$ and $\bar{\Pi}_h$ in the Fourier domain that can then be used in (2.11), (2.12), (2.14) and (2.15) to solve for the fields in the Fourier domain. By enforcing the boundary condition on each anisotropic layer and using Galerkin's method [4] we can solve the resulting immittance functions for the surface currents on each conductor. The input impedance can then be calculated using [20]

$$Z_{in} = -\frac{1}{I_0^2}\int_0^d \bar{E}_y \cdot dy \tag{2.17}$$

where I_0 is the probe current, d_{12} is the length of the probe and $\bar{E}_y$ is the field at the port. As mentioned before, Oliveira and d'Assuncao [20] show for the first time in 1996 that this method can be used to solve for the input impedance of an isolated microstrip antenna in multiple anisotropic layers. In this work we will extend this method to solve for the mutual impedance between elements in layered anisotropic structures for the first time. At this time it is anticipated that an application of (2.17) will be used in the following manner:

$$Z_{mutual} = -\frac{1}{I_0^2}\int_a^b \bar{E}_y \cdot dy \tag{2.18}$$

where the integral is evaluated over the other port of interest in the mutual coupling. (2.18) is essentially evaluating $Z_{ba} = V_b/I_a$ and is similar to the expression in (1.10).

b) *Advantages/Disadvantages*

Although the derivation of the immittance functions is lengthy they do result in nice algebraic expressions that are easily implemented in a numerical method. The only draw back in the numerical method is the infinite integration in the spectral domain. Nelson [16] has shown that this integration can be terminated at $500k_0$, where $k_0 = \omega\sqrt{\mu_0\varepsilon_0}$, thus allowing for a fast integration routine.

4) *Other methods*

Other methods such as the transmission line model and cavity model [11] can be used for evaluating input impedance. But these methods do not rigorously account for the surface waves on the antenna substrate and do not account for mutual coupling between closely packed elements.

5) *Chosen method*

From the above discussions we can see that the expressions in *the exact green's function method for a grounded dielectric slab* require a derivative approximation and infinite integration. Even though this method has been shown to provide accurate calculations for microstrip antennas in multiple anisotropic layers the numerical implementation can be quite extensive.

We have also seen that infinite integration is required in *the equivalent magnetic source method*. Even though this method has been shown to accurately calculate mutual impedance between microstrip antennas on isotropic substrates more work would need to be done to determine if the method could evaluate problems in multiple anisotropic material.

Other methods such as the transmission line model and cavity model were also discussed. As mentioned above these methods do not account for surface waves and mutual coupling between elements. Thus, more development would be needed to determine if the questions proposed above could be answered with either of these methods.

Also from the above discussion we have seen that *the spectral domain immittance* *method* has an extensive derivation process that yields much simpler expressions. One major advantage is not needing to evaluate the derivatives on the surfaces. Even though the method requires an infinite integration we have seen that by truncating the integration in an efficient manner we can perform calculations quickly and evaluate problems accurately. Also, Oliveira and d'Assuncao [20] has shown that the spectral domain immittance method can be used to solve for the input impedance of an isolated microstrip antenna in multiple anisotropic layers. It is anticipated that solving for mutual impedance between printed antennas in multiple anisotropic layers is a computation that can be realized. Therefore, for the work proposed here *the spectral domain immittance method* will be used to calculate the input and mutual impedance of printed antennas in multiple anisotropic layers.

Technical Objective 3: Validate numerical calculations

Once the spectral domain immittance method has been implemented in Matlab [63] the computed input and mutual impedance values for several problems will be compared to the calculations from the commercially available software program Momentum in Advanced Design System (ADS) [64] and results found in previous literature. Momentum allows the user to enter problems with planar conductors on multiple isotropic layers. This comparison is a simple and intermediate step between the new Matlab code and measurements and will be performed for several of the printed antennas mentioned above.

The first problem will be a single printed dipole on an isotropic substrate. The geometry will be similar to the dipole found in the work by Rana and Alexopoulos [10] and is shown in Figure 13 a). The input impedance calculations of the new code will be compared to the computations by Momentum and Rana and Alexopoulos [10]. This will be a significant first step in the development of the new code by showing that the extensive computations are accurate. It will also show that the use of Momentum is also an accurate tool for problems in the research proposed here. The second problem will be the computation of the mutual impedance between two printed dipoles on an isotropic substrate. The geometry of each dipole is shown in Figure 13 b) and is similar to the printed dipoles found in the work by Alexopoulos and Rana [22]. The results of the new code will then be compared to Momentum and the computations in [22] for several different antenna orientations (broadside, colinear, ...etc).

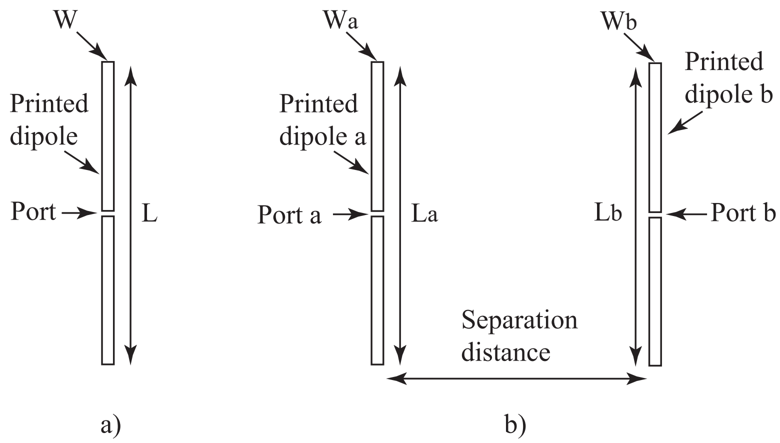

Figure 13. (a) printed dipole on an isotropic substrate; (b) two printed dipoles on an isotropic substrate.

The third problem will be a single rectangular microstrip antenna on an isotropic substrate. The geometry will be similar to the antenna found in the work by Pozar [11] and is shown in Figure 14 a). The new code using the spectral domain immittance method to calculate the input impedance of the rectangular microstrip antenna will be compared to the computations by Momentum and measurements by Pozar in [11]. This will show that the new code can be used for rectangular microstrip antennas. The fourth problem will compute the mutual impedance between the rectangular microstrip antennas on an isotropic substrate shown in Figure 14 b). The geometry will be similar to a problem found in work by Pozar [11]. The new code calculating the mutual impedance between the rectangular microstrip antennas will be compared to the computations by Momentum and measurements by Pozar in [11].

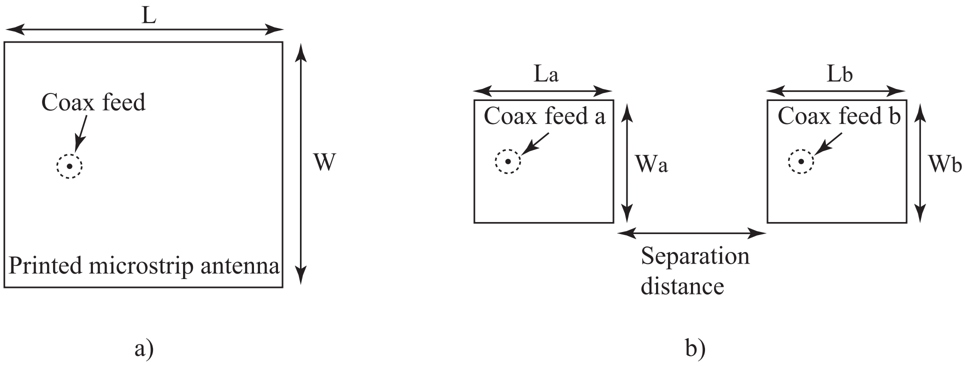

Figure 14. (a) rectangular microstrip antenna on an isotropic substrate; (b) two rectangular microstrip antennas on an isotropic substrate.

Many significant results will be obtained by looking at the four problems mentioned above. First, by computing the input and mutual impedance values for the dipole problems in Figure 13 we will see that the very extensive new code making the computations is accurate, the method of using (2.17) is correct, the method of using (2.18) for the first time is also correct and that Momentum is an accurate tool for this research. Second, by computing the input and mutual impedance values for the rectangular microstrip antennas in Figure 14 we see that the new code can be used to evaluate problems with rectangular geometries. This is very important because it lays the foundation for answering the proposed questions.

Technical Objective 4: Design and build a measurement setup to validate the numerical results.

The work presented by Jedlicka, Poe and Carver [24] for measuring the coupling between microstrip antennas will be used to validate the results from the new code. The bottom layer will be attached to the aluminum ground plane and multiple layers will be stacked to correspond appropriately with the problem of interest. Because of the availability of material the initial measurements will be performed exclusively with isotropic material. Once these measurements correspond with the numerical results from our new code a step towards anisotropic material will be taken. Many different types of anisotropic material exist, such as Epsilam 10, Teflon, single-crystal sapphire and boron nitride [2] and it is believed that this type of material is available from board manufacturers such at 3M, Arlon, Metclad or Rogers. This will be very useful for validating the numerical results used to compute mutual coupling between various antennas.

2.4. Initial work

The steps for deriving (2.11)-(2.16) and the immittance functions in [16] are quite extensive and have already been undertaken by the PI. In addition, a complete derivation of the method has been carried out to ensure that the PI understands the underlying principles. For sake of length they have not been shown here. At this point the PI has also started writing Matlab code to evaluate the immittance functions in [16].

CHAPTER 3. SIGNIFICANCE OF ANTICIPATED RESULTS

It is expected that the input impedance of the driven element in Figure 12 will be significantly effected by the mutual impedance with other driven and parasitic elements in the structure. This effect on input impedance should be significant for elements close to any driven elements. But based on comments by Krowne [17] and work by Wang [62] it is anticipated that by choosing the appropriate values of permittivity for the anisotropic material the mutual impedance between the elements can be minimized. Also, proper placement of the conducting elements on different anisotropic layers is expected to reduce the coupling and have minimal impact on the performance. In some cases it is expected that the actual surface area of an array could be reduced without effecting the performance. This could be done by proper values of permittivity and design freedom to place certain driven elements on other anisotropic layers.

The work here only looks at very specific types of antennas. This work could easily be extended to include some of the new dual frequency antennas, UWB antennas, various arrays, and various types of materials such as metamaterials. This work could also be extended to look at problems with many RFID tags in a small area. In this case the close proximity of the tags results in significant mutual coupling and thus directly effects the power harvesting capabilities and the read range of each tag. Also, using anisotropic material as substrates and superstrates for an RFID tag could be another possible area of research.

CHAPTER 4. CONCLUSION

A procedure for studying the input impedance and mutual coupling of microstrip antennas on multiple anisotropic layers has been presented. It is suggested that the spectral domain immittance function technique can be used to calculate the input impedance and mutual coupling of a driven element on multiple anisotropic layers. It is anticipabed that the accuracy of the results will be verified using numerical calculations in Matlab, as well as commercially available code and a measurement procedure that will be employed for the first time with multiple antennas on multiple anisotropic layers.

Many areas such as microstrip arrays, RFID and EMC deal with mutual coupling in each design. It is anticipated that this work dealing with input impedance and mutual coupling will lay the ground work for future efforts that can include more general cases.

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