

Antennas for Millimeter-Wave Applications

by

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ABSTRACT

Migration of wireless systems to millimeter wave frequencies requires cost reduction solutions that take advantage of the compact size, high bandwidth and extreme data rates that a high frequency operation offers. New materials with better mechanical, thermal and electrical properties are now available; fabrication processes have reached nanometric resolutions and depending on the antenna's type, different properties can be enhanced. Multiple applications had been created around this technology, internet of things, imaging technology, biomedical applications and interferometry radars base its operation in this technology.

This dissertation shows contributions in the measurement and fabrication of millimeter wave antennas. A tunable matching network is proposed to measure planar antennas. The method is used to measure antennas fabricated on wafer and on PCB technology without the need for additional test fixtures. Regarding fabrication technologies, this thesis demonstrated the feasibility of using multilayered polyimide films to serve as the substrate for an antenna, thus being able to integrate it in a traditional CMOS process. DuPont polyimide PI2611 has a CTE of 3ppm/.C which is very close to the CTE of silicon (2.3ppm/.C) making it suitable as an interlayer in the development of antennas for in-package technology.

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"In the end, though, maybe we must all give up trying to pay back the people in this world who sustain our lives. In the end, maybe it's wiser to surrender before the miraculous scope of human generosity and to just keep saying thank you, forever and sincerely, for as long as we have voices" – Elizabeth Gilbert.

DEDICATION

This thesis work is dedicated to my family, Miriam, Jorge, Laura, and Fernando who has been a constant source of support and encouragement in my life.

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Chapter 1

INTRODUCTION

1.1 Motivation

The Internet of Things (IoT) is the most significant trend in technology today; different industries such as energy, healthcare, and automotive are incorporating "smart" devices to improve user-machine and machine-machine interaction. This new market has created new requirements in speed and bandwidth that current technologies can hardly cover; the industry needs a way to increase channel capacity in wireless communications since the current ones are too crowded to be useful. Take, for instance, the users of wireless local area network (WLAN) and wireless personal area network (WPAN) protocols, which share the same spectrum and most of the time collide and interfere with each other. Thus, many research groups are proposing the migration of wireless systems to millimeter-wave frequencies (30 GHz – 300 GHz) as a feasible solution to these problems.

At millimeter-wave frequencies wider bandwidths and higher data rates can be achieved. This range provides the speed and capacity that these new applications require; moreover, the corresponding wavelengths (5mm @ 60GHz for instance) make the integration of antennas in RF-Chips possible, while also allowing the use of transmission lines as a replacement for inductors and capacitors in a circuit; in other words, matching elements and resonant structures can be used in ways that are impossible at 2.4GHz to 5GHz.

An increase in the operating frequency, however, is a real challenge because it is necessary to deal with undesired effects which are generally neglected at low frequencies. During circuit design it is crucial to consider the bandwidth of the different components integrating a communication system, since materials and solutions commonly used for low frequency designs might not work or might not be feasible at millimeter-wave frequencies. As the frequency increases, model and component reliability are questioned; electromagnetic simulations represent a challenge since it is common to run into convergence problems and long simulation times. Furthermore, fabrication technology has to be carefully chosen since the smallest change or error in device dimensions may lead to a significant deviation in the device's performance.

The aim of this dissertation is to propose methodologies and strategies to enrich the research of antennas at millimeter-wave frequencies; first, a study of different alternatives in antenna design and fabrication technologies are presented; the chosen simulation and fabrication methodologies are then analyzed; and finally, the measurement results of different prototypes are discussed. As a consequence, clear guidelines to determine antenna impedance and polarizations are developed and analyzed.

1.2 Research Objectives

This work was undertaken with several objectives in mind, all oriented to adding knowledge to the field of integrated millimeter-wave antennas, since technological development is leaning towards Antenna in Package solutions for many high-frequency applications. The main contributions are the following:

- To propose strategies and methodologies to design antennas at millimeterwave frequencies, including an analysis of different planar antennas and the development of equivalent circuit models to emulate the behavior of antennas operating at high frequencies.
- To analyze fabrication technologies in order to choose a reliable process at millimeter-wave frequencies; including the fabrication of planar antennas employing different manufacturing processes and the analysis and correlation of experimental data with the ones obtained using the proposed design.
- To analyze and develop strategies to measure antenna impedance using the equipment available at INAOE's Microwave Laboratory; it requires the study of different approaches used previously and the measurement of different prototypes.

1.3 Methodology

To develop this work, the following steps were considered:

- a) A state-of-the-art review of the most common techniques and materials used to develop antennas at millimeter-wave frequencies; this review includes related works on dielectric materials used to develop antennas, deembedding techniques to measure antenna impedance, and approaches to change antenna's polarization from linear to circular one.
- b) Selection of a proper substrate in order to ensure good performance at low cost for antennas operating at high frequency.
- c) Designs of planar antennas and feeding lines. For this step, the work relied on High Frequency Simulator Structure (HFSS) to estimate the antenna's performance and validate the first approaches based on basic antenna behavior.

- d) The Antennas manufacturing process. For this step, the methodology to develop antennas using the technology and tools available at INAOE Microelectronic laboratory was defined.
- e) Antenna's Impedance Measurements. It includes one-port measurements of manufactured antennas using a Vector Network Analyzer working in the frequency range of 44 MHz 67 GHz.
- f) Analysis of Results, correlating experimental and theoretical results.

The methodology presented here was used in designs in Printed Circuit Boards (PCB) technology as well as in Silicon technology.

1.4 Organization of this document

This document is divided into six chapters as follows:

- Chapter 1 summarizes the benefits and challenges in the design at millimeter wave frequencies, its relation with this work and presents the research objectives and methodology followed in this thesis.
- Chapter 2 presents a general description of millimeter-wave planar antennas; this description includes basic characteristics of slots and patch antennas, the main losses mechanism, related works, and applications to this technology.
- Chapter 3 details the technological approaches explored in this thesis, it considers pros and cons of each of them, including simulations and experimental tests obtained through this work.
- Chapter 4 shows the impedance measurement process for planar antennas used in this thesis. First, the equipment and parameters necessary to make high-frequency measurements for Monolithic Microwave Integrated Circuits (MMIC) are reviewed. Then, this process is adapted to get an effective way to do antenna impedance measurement using RF-probes. Finally, the proposed method is validated through the measurement of two antennas on PCB and on-wafer technology.

- Chapter 5 gives an introduction to antenna polarization and shows the design and validation of a circularly polarized coplanar patch antenna for 60 GHz; in this case, a change in the feeding point modifies the antenna's polarization from linear to circular one, this change enhanced the performance of this device, since in a circularly polarized patch two orthogonal modes are excited; and dual band operation can be easily created by employing a rectangular patch instead of a square one.
- In chapter 6, the conclusions and future work are described.

Chapter 2

MILLIMETER-WAVE PLANAR ANTENNA

2.1 Introduction

Migration of wireless systems to millimeter wave frequencies requires cost reduction solutions that take advantage of the compact size, high bandwidth and extreme data rates that a high frequency operation offers. Planar antennas are highly regarded to cope with these constrains, they are compact and light, its fabrication process is simple, it can be done by using metallic ink [1] or using photolithography and wet etching processes; these features give versatility in design and endorse their functionality since they could be mass produced, supplying the actual demand of wireless system.

Extensive research looking for compatible technology at millimeter-wave frequency promotes improvements in different fields: new materials with better mechanical, thermal and electrical properties are now available; fabrication processes have reached nanometric resolutions and depending on the antenna's type, different properties are enhanced; finally, simulation tools are more reliable and fast, allowing full-wave electromagnetic analysis within a reasonable amount of time. Multiple applications had been created around this technology, internet of things, imaging technology, biomedical applications and interferometry radars base its operation in this technology [2].

This chapter presents general theories for planar antennas; it includes a review of the degradation mechanisms in the performance of millimeter-wave planar antennas, and also shows an overview of the different approaches taken in the development (material choices for millimeter wave operation), measurement (de-embedding techniques) and design (changes in antenna's polarization) of millimeter-wave planar antennas.

2.2 General Description

Planar antennas are basically flat metallic structures built over dielectrics, they have essentially changed the microwave and millimeter-wave communication industry because they can be mass-produced at a much lower cost than other antennas, their planar feature make them lightweight and compact easing integration to other components on a communication system. Planar antennas can be divided into two groups: Patch and Slot antennas, they are described in the following sections.

2.2.1 Patch Antennas

Patch antennas in its simple configuration consist of two metal layers (radiated element and ground plane) separated by a dielectric (substrate). Most of these antennas are monopoles that unlike a dipole that needs two identical rod conductors to produce radiation, they have a ground plane above them that is part of the device; in a monopole, radiation is produced by fringing fields around a conductive patch [3]. The easiest way to analyze monopole antennas is through its dipole counterpart, because dipoles have been extensively studied and their equations are well known.

Using the image theory and considering that the ground plane is large enough, the fields above the ground plane are similar to the ones produced by reflections from the ground plane, they will seem to come from an image antenna forming the missing half of the dipole, in *Figure 2.1* an example of the fields for a monopole and its equivalent dipole illustrate it, therefore a monopole can be analyzed in terms of its dipole version.



Figure 2.1 Equivalency for Monopole Antenna; (a) Fields in a triangular Antenna and (b) Fields in its equivalent dipole (bowtie antenna)

Monopole antennas are about half of its dipole counterpart, its radiated pattern is very similar, but because a monopole radiates only into the space above the ground plane, directivity and gain is double the one obtained in a dipole antenna twice the length. Finally, given that only half voltage is required to drive a monopole antenna the same current as in a dipole, the input impedance is half of that of a full dipole antenna. Thus a quarter-wave monopole has a gain of 5.19dBi and an input impedance of $Z_{in} = 36.5 + j21.25 \Omega$ in the free space [3].

2.2.2 Slot Antennas

A slot antenna is a structure formed by removing a regular shape (rectangular, circular, triangular, etc.) from a metallic sheet (Figure 2.2*a*). These antennas were first introduced in 1972 and were popular because their nature gives them additional design variables, in this case, their radiating features is not only determined by their slot size and shape, but also their position and feeding orientation will determine how they radiate.

The antenna in Figure 2.2*a* is more efficient than the antenna on Figure 2.2*b* since, the slot antenna has a wider metallic conductor, and when the current passes through it, the current spreads out over the sheet reducing joule heating effect. However, the antenna shown in Figure 2.2*b* consists of two resonant stubs joined to a coplanar waveguide transmission line, it has end conductors that carry currents in the same phase and produces radiation, but not efficiently because the short pieces of metal enhance joule heating and current crowding.

Slot antennas can be analyzed through an extension of Babinet's principle for electromagnetic fields [3]. It was developed by Henry Booker and states that radiated fields of an antenna and its complementary counterpart (device formed when the conductive material and dielectric material are interchanged) act in the same way that the fields in the media in which the structure is immersed; therefore, the fields of the slot antenna (\vec{E}_s and \vec{H}_s) are related to the fields of its complement (\vec{E}_d and \vec{H}_d) through eq. (2.1) and (2.2); the impedance of slot antennas (Z_{slot}) can be obtained through the impedance of its dual (Z_{dipole}) and the intrinsic impedance (η) using eq. (2.3) [3].

$$E_{\theta S} = H_{\theta d} ; E_{\phi S} = H_{\phi d}$$
(2.1)

$$H_{\theta S} = \frac{-E_{\theta d}}{\eta^2}; \ H_{\phi S} = \frac{-E_{\phi d}}{\eta^2}$$
(2.2)

$$Z_{dipole}Z_{slot} = \frac{\eta^2}{4} \tag{2.3}$$

Hence, the antenna's fields can be inferred from its complementary antenna's fields; furthermore, other features like the antenna's impedance, radiated pattern and polarization can be obtained through this principle; in the case of polarization it is reversed; if the dipole is vertically polarized its counterpart slot antenna will be horizontally polarized and vice versa.



Figure 2.2 Example of Coplanar Antennas: Slot Antenna (a) and its Complementary Antenna (b)

2.3 Degradation mechanisms in millimeter-wave planar antennas

To develop efficient radiators at millimeter wave frequencies, some effects inherent to development of devices operating at high frequencies must be taken into account:

2.3.1 Conductor Losses

In a conductor, there are several mechanisms of energy dissipation; at low frequencies the joule effect is dominant, it occurs when an electromagnetic wave propagates along a conductor, in this case, the electrical resistance of the conductor induces ohmic heating on it; at high frequencies in addition to joule effect there is a change in current distribution along the conductor, this change involves two additional effects: *The Skin Effect* and *The Current Crowding*.

Skin effect produces an increase in the effective resistance proportional to the square root of frequency; this effect is normally taken into account for frequencies above 2GHz, because below it, the trace thickness is typically less than or equal to the skin depth [4].

Current crowding is a strong function of frequency, resulting in effective resistance increases at a concave function higher than the linear rate observed in skin effect [4].

2.3.2 Substrate Losses

In substrates there are also losses associated with frequency, they are described below.

Dielectric Polarization: once the material is polarized, the dipole moment formed in the dielectric, starts to oscillate at the operating frequency; this energy dissipation is an additional source of signal attenuation at high frequencies. To include this effect, a complex permittivity was defined. It is specified in datasheets through the loss tangent or dissipation factor, which is a parameter that measures the isolation degree of this material, the lower it is, the better the isolation.

Eddy Currents: If a semiconductor is used as a substrate the eddy-current losses needs to be taken into account. Eddy currents in this material arise from the magnetic field generated by the antenna and the free electrons in semiconductors. Once these magnetic fields penetrate the material, they induce parasitic currents along the width and thickness of the substrate.

Strong Capacitance: In the antenna's design one critical parameter is the dielectric constant because it establishes how strong the electric field inside the substrate will be. For high dielectric constants (i.e. 11.9 for silicon) it is less likely that the energy generated by the source will be converted to radiation, making them poor radiators.

2.3.3 Spurious Emission due to feeding lines

Antenna feed lines have discontinuities that introduce undesired radiation and interfere with its normal operation; these discontinuities are formed in the transition between the transmission line and the antenna, therefore a careful selection of the feed line must be done in order to prevent it.

To illustrate this problem, a rectangular patch antenna with a quarter wavelength transformer was designed and simulated for 60GHz operation over a low loss substrate (Rogers 4003C). Figure 2.3a shows full wave simulations of the electric field in the rectangular patch designed on a thicker substrate (h = 0.8mm). Note that the width of the resultant transmission line has similar dimensions to the antenna's patch. Therefore, a high spurious emission is expected; However just by changing the thickness of the substrate, this problem is reduced, Figure 2.3b shows the electric field when the thickness of the substrate is four times thinner (h = 0.2mm), with these dimensions the feed line is thin and all the energy concentrates in the patch.



Figure 2.3 Comparison of Electric Field in a 60 GHz Rectangular Patch Antenna: (a) Thicker substrate h=0.8mm, (b) Antenna over a substrate of h=0.2mm

2.4 Related Works

This thesis proposes improvements in the development, measurement and polarization of millimeter wave planar antenna; consequently it is necessary to assess relevant work conducted in these three areas.

2.4.1 Dielectric Materials at Millimeter Frequencies

Polymer films are an excellent choice to cope with the strong requirements when working at millimeter frequencies, they have excellent mechanical and electrical properties and have been extensively used in the conformal coating to protect printed circuit boards from moisture, dust, corrosion, abrasion, and other environmental stresses [5]. Below a review of the most popular materials is presented.

- ✓ Photoresist-Based Polymer SU-8 2000 has been proposed as a low-cost material for millimeter-wave circuits due to its good electrical and mechanical properties; it has a dielectric constant (ε_r) of 3.0 and a loss tangent of 0.04; and has been used to build antennas, inductors and resonators [6, 7] in frequencies from 26GHz to 140GHz. However, in many of these works this material was used as flexible substrate completely independent of the chip or it was integrated into the chip thereby an additional structure that supports the whole system like the silicon interposer proposed in [8] which ended increasing the total area and the fabrication cost.
- ✓ *Parylene*, a liquid crystal polymer (LCP), has been used as another option for a flexible substrate for microwave and millimeter-wave applications and has shown low relative dielectric constant $\varepsilon_r \approx 2.4$ and low loss characteristics measured by loss tangent $tan\delta \approx 0.0006$ [9]. The potential in the development of antennas has been proved in [10] where a flexible antenna for WLAN and UWB applications was developed.

- ✓ *Elastomeric polydimethylsiloxane (PDMS)* is another material with proper electric and mechanical properties for millimeter wave circuits, it has $\varepsilon_r \approx 2.67$ and $tan\delta \approx 0.04$, and has been used mainly in the development of membranes for ultra-flexible millimeter-wave printed antennas thanks to its extremely low Young's modulus < 2MPa. In [11] this material is used for the development of a millimeter-wave ultra-flexible micro-machined antenna, in [12] an array of rectangular patches is implemented, and in [13] an inflatable antenna is proposed, the air gap is altered and it changes the antenna's electrical features.
- ✓ Benzocyclobutene (BCB), on the other hand, having a low dielectric constant equal to 2.65, and a low loss tangent equal to 0.0008 at 1 GHz, with a stable dielectric behavior over a broad frequency range, up to 1THz is the preferred option; many works show its use directly on wafers or on micro-machined designs. In [5] a 60GHz microstrip array was developed; in [14] an antenna based on a BCB-Si interlayer was proposed, this design employed a substrate integrated waveguide (SIW) as a feeding line; [15] presented antennas on micro-machined silicon-BCB membranes coupled with a T-shape microstrip feeder, and finally [16] showed another antenna using a quarter wavelength transformer to match the antenna's impedance.

2.4.2 De-embedding of Millimeter Wave Antennas

Millimeter-wave antennas present unique challenges regarding the measurement of its performance parameters, at high frequencies it is necessary to deal with undesired effects neglected at low frequencies and then connections to measurement equipment introduce significant losses and discontinuities that must be considered when modeling the whole system.

In general, the use of pad structures introduces parasitic effects that impact the *S*-parameters measurements of the antenna. De-embedding techniques have been proposed to extract the effect of pads in the *S*-parameters measurements.

Computational Method: In [17] a computational method for de-embedding of connector response is introduced, in this case, a precise numerical model through the Method of Moments (MoM) is used to obtain the response of multiple cases to get enough data to calculate the connector response.

Balun and test structures: This is the most common technique, in this case, a completely planar transition is designed to transform impedances and match the system, and it is also necessary to include three different structures (i.e., an open, thru and line configuration) to remove the effects of pads. Below a description of previous works is detailed.

In [18] an antenna is measured using RF probes and a structure composed by a balun and a CPW to MS transition. In a post-processing step, the effect of this structure is de-embedded from the measurements using test structures.

In [19] a balun structure was created to test differential antennas with standard measurement equipment, the balun makes the conversion from CPW to CPS mode; however, to get proper measurements, additional structures for calibration and de-embedding were created, these structures give additional data that helps to estimate balun response.

To sum up, conventional de-embedding methods use measurements on specific test structures to remove parasitic effects resulting in additional post-processing work and a wider test-chip area. This thesis, however, presents a technique to measure on-wafer in-package antennas employing only RF G-S-G probes, no additional test structure or de-embedding methods are required; this method uses a coplanar waveguide transmission line to match the antenna to ground-signal-ground probes.

2.4.3 Antenna's Polarization

Polarization is an antenna's feature that can be modified using additional feeding sources or changing the antenna's type. Planar antennas typically exhibit linear polarization, however circularly polarized (CP) antennas offer more advantages; they are less affected by multi-path interferences or fading [20], they are able to eliminate polarization mismatch losses caused by Faraday's rotation in small satellites [20, 21] and in some cases it leads to a size reduction compared to conventional patch antennas (in [22] it is about 36%, in [23] they achieve 42%).

In order to achieve circular polarization, it's necessary to create electromagnetic perturbations that ensure the propagation of two orthogonal modes in the patch. This condition can be met by multi-feed arrangements or by single-feed techniques where slight modifications made to the antenna's elements (i.e. slightly changing the patch shape or removing part of it) induce orthogonal electric fields [3, 20]. In single-feed approach, the antenna has an asymmetric feeding in order to induce circular polarization as is indicated in different works [24].

At 60GHz, examples of circular polarized antennas can be found, in [25] a 60-GHz wideband circularly polarized (CP) helical antenna array over a low temperature confired ceramic (LTCC) technology is presented. In [26] a microstrip dual feeding (quadrature hybrid coupler) is used to produce a dielectric rod antenna with circular polarization features. In [27] a circularly polarized antenna array fed with an SIW is realized for PCB technology.

In chapter 5 modifications in the feeding of a Coplanar Patch Antenna (CPA) are implemented to produce a circularly polarized microstrip patch antenna with dual band operation.

2.5 Applications

The millimeter wave spectrum is attractive for many industries, such as the automotive industry, where the high data rate can be used to have a real-time radar system that allows intelligent highway programs and low-cost autobraking and safety measurements for vehicles; another interesting application is in digital television, the high definition video could be transmitted using a wireless solution replacing the actual HDMI cable; and also imaging technology has been changing the medical industry, creating new devices to detect different fixtures [28].

Finally, two standards for the wireless communication technology operating over the unlicensed 60 GHz frequency band were already proposed. They were created by a consortium of technology companies; Ultra-Gig was a pioneer in 2008 but then, two years later, the IEEE and Wireless Gigabit alliance created the IEEE 802.11ad protocol [29].

2.6 Chapter Review

This chapter presents basic concepts of millimeter wave antennas; it includes a description of different antenna types, its advantages, electrical characteristics and the performance degradation mechanisms that millimeter wave operation produces. Once risks and advantages of planar technology were assessed, previous works related with the main contributions of this thesis were presented.

In relevant works, a study of suitable substrates for millimeter wave antennas was discussed, followed by an overview of de-embedding techniques applied to millimeter wave antennas and a review of the common methods used to change the antenna's polarization at high-frequency operation. Regarding substrates choices, despite each of them having excellent electrical properties, the high losses induced at high frequency and the constant thermal changes that these circuits may be exposed to needs to be considered to propose a feasible option. In chapter 3 different alternatives are explored.

From the study of previous works related to the antenna's measurements, there is not a unified technique, although in general, they use de-embedding and test fixtures to have acceptable levels of attenuation, the measurement process depends on the antenna's type and technology, they propose its own technique and test structures, there is not a standard and therefore, the level of precision varies depending on the author and most of them don't mention the feeding line. In chapter 4, a different approach is proposed.

Finally, changing the antenna's polarization may improve some of its features, in section 2.4.3 the advantages in size reduction and possible applications for circularly polarized antennas were given; still, most of them have complex designs to achieve circular polarization. In this dissertation, a much simpler approach is analyzed; full wave simulations illustrate the advantages and possible application (more details in chapter 5).

Chapter 3

TECHNOLOGY OPTIONS FOR MILLIMETER WAVE ANTENNAS

3.1 Silicon Micromachining

The micromachining technique consists of removing part of the substrate in order to create a media where the effective permittivity is reduced in comparison to the effective permittivity of high index substrates like silicon wafers. This condition improves the antenna's performance (a 64% increases in bandwidth has been reported, with an efficiency of 28% [30]).

The material is laterally removed under the patch forming a cavity which consists of a mixed region of air and silicon; depending on the amount of substrate removed, the effective permittivity is changed. These antennas are known as MEM Antennas and since 1998 they have been studied as a practical solution, next section presents a review of them.

3.1.1 Related Works

In 1998 a duroid membrane was used as support for a rectangular patch antenna, its performance was compared with regular designs on high and low index materials, it shows similar results as the structure build over a low index duroid [30]; in 2006 a silicon antenna was built, this time, they worked at Kaband and used etch technique to produce the air cavity [31]; in 2008 another example operating in Ka-band is presented, in this case, the thickness of membrane is analyzed [32]; in 2009 a millimeter-wave microstrip antenna array is developed, they used a polymer to produce the membrane and scales to 60GHz [33]; in 2010 another approach at 60GHz was presented, bandwidth improvements and new materials were used (Benzocyclobuten dielectric) [34].

However, design procedure presented in above experimental approaches doesn't contemplate the influence of cavity dimensions on antenna's parameters; it is an important parameter that compromises the real size of this antenna, they only mention that it affects the antenna's efficiency and usually oversize it (In [34] they employed 13.14% of the total cavity's area, in [30] was 23.14%, in [33] 44.01% was used and 71.31% was used in [31]). The next section presents a study of this parameter; the size and characteristic of such cavity were modified in order to analyze their influence in the antenna's performance.

3.1.2 Influence of Cavity Size in Antenna's Performance

3.1.2.1 Antenna's Design

Figure 3.1 shows the transversal section of a micromachined rectangular patch antenna.



Figure 3.1 Schematic of the antenna's transversal section
Permittivity of Compound Region:

Using the cavity model for a rectangular patch antenna it is possible to estimate the effective dielectric constant of the compound region (ε_{cavity}), as is detailed in [30, 31]. The permittivity of this region is calculated from the following expression,

$$\varepsilon_{\text{cavity}} = \frac{\varepsilon_{\text{air}} * \varepsilon_{\text{sub}}}{\varepsilon_{\text{air}} + (\varepsilon_{\text{sub}} - \varepsilon_{\text{air}}) \left(\frac{h_{\text{air}}}{h_{\text{sub}}}\right)}$$
(3.1)

Where ε_{air} and ε_{sub} are the permittivity of air and silicon respectively, the thickness of the cavity is h_{air} and substrate thickness is denoted by h_{sub} . Considering the following patch dimensions, $h_{sub} = 270 \mu m$, $h_{air} = 132 \mu m$, $\varepsilon_{air} = 1.006$ and $\varepsilon_{sub} = 11.9$ the permittivity of this region is: $\varepsilon_{cavity} = 1.9105$.

Patch Dimensions

Once the relative permittivity of the compound region is known, it is possible to use the traditional transmission-line model to design a rectangular patch antenna to estimate its size. In Table I, the design parameters and dimensions of the patch are shown [35].

Design Parameters	Patch Dimensions
fr = 30GHz	Width (W) = 4.5mm
$E_{sub} = 11.91$	Length (L) = 3.42mm
$h_{sub} = 0.275 mm$	

Table I. Antenna's Parameters

Feeding Line Dimensions

In this case, a transmission line and a quarter wave transformer were used to match the antenna's and transmission line impedance, since the feeding line had to be connected directly to the antenna, most of the energy would be reflected given that the antenna's characteristic impedance is about 232 Ω and the line's impedance is 50 Ω , these estimations were done following the design methodology presented in [35]. In Table II, a summary of the dimensions of these elements is presented.

Table II. Feeding Line's Dimensions

Feed-Line	Width [mm]	Length [mm]
Lambda quarter transformer	0.22	0.9
Transmission Line	0.1	0.92

3.1.2.2 Simulations

To analyze the influence of the cavity's size on the antenna's electrical characteristics, three simulations for a micromachined rectangular patch at 30GHz were performed. First case (Case A), the antenna is simulated as if it were built on the surface of a uniform dielectric material with a relative permittivity equivalent to 1.9105. This simulation is the antenna's expected response. Then, the compound region is analyzed, first for an air-cavity that is made right under the patch (Case B) and for a wider air-cavity that extends well beyond the patch (Case C).

Simulations were done using a full-wave 3D Field Solver, Figure 3.2 shows the S_{11} parameter for each case, this data gives an idea of how close our design is to the expected resonance frequencies and the degree of coupling between the feed-line and the antenna, lower reflections at resonance frequency indicate a good matching, meaning all the energy is being delivered to the antenna. Figure

3.3 presents a 3D representation of the radiated pattern in the far field and Figure 3.4 illustrates how the electric field interacts with the air-cavity.



Figure 3.2 Reflection Coefficient: (a) Material with effective permittivity; (b) Cavity just under the patch; (c) Cavity extended beyond the patch.



Figure 3.3 Radiated Pattern: (a) Material with effective permittivity; (b) Cavity just under the patch; (c) Cavity extended beyond the patch.



Figure 3.4 Electric Field Interaction: (a) Material with effective permittivity; (b) Cavity just under the patch; (c) Cavity extended beyond the patch.

3.1.2.3 Conclusions

The results of these simulations show that cavity size has a large influence on the behavior of the antenna. In all three cases, the goal frequency was 30GHz. In Case (A), the cavity is considered through the equivalent permittivity, as shown before. The resonant frequency is near the goal frequency, and the radiation pattern presents only a principal lobe in each, the Magnetic Plane and the Electric Plane. Making the cavity larger shifts the resonant frequency to a lower range, it means that Eq. 3.1 fails to estimate a proper permittivity, from these simulations the effective permittivity must be higher than the estimation, also a little mismatch in the feeding line produces a lower reflection coefficient. In Case (B), the radiation patterns start to present secondary lobes, and the symmetry in the Electric and Magnetic Planes is lost. Under Case (C), which has a larger cavity under the patch, the reflection coefficient improves, and the radiation pattern regains some of its symmetry, but it presents, albeit small, secondary lobes. Therefore, It's difficult to estimate a useful effective permittivity, In Case B and Case C an antenna with the same features is simulated with only cavity size as variable but even so, it changed their resonance frequencies and radiated patterns. Also, these technology options introduce new challenges because the real size of the overall device is affected; in general, a wider cavity offers the best results, as far as this study reaches.

3.2 PCB Trace Antennas

A PCB trace antenna is an antenna implemented as part of the printed circuit board (PCB) manufacturing process, it allows lowering costs because it is a fast and consistent way to make antennas in a high volume manufacturing environment, this accurate and reliable process provides a feasible method of wireless communication. Regarding high frequencies issues, high-quality materials have been developed, they offer excellent mechanical and electrical properties that can be useful at millimeter-wave frequencies. In this dissertation a laminate of RO4003C is used, this material is a composite material composed of a ceramic-filled, highly cross-linked, hydrocarbon thermoset resin coated on woven glass. This combination provides the electrical performance of PTFE/woven glass with the same processing method as standard epoxy/glass. The end product is a laminate with controlled dielectric constant and low dissipation factor, for RO4003C $\varepsilon_r = 3.38 \pm 0.05$ and $Tan\delta = 0.0027$ @ 10GHz [36].

In order to choose a proper fabrication method for the development of millimeter-wave antennas, different approaches were evaluated, they are presented in the next subsections.

3.2.1 Isolation Milling

Prototyping by isolation milling is a fabrication process that consists of removing areas of copper from a sheet of printed circuit board material to recreate the structures patterned in the layout using a precise numerically controlled multi-axis machine tool and a special milling cutter. The accuracy of this technique depends on different variables such as end mills size, vibration, position in the laminate, layout size, etc. Therefore, it is difficult to estimate if this method is useful for fabrication of millimeter-wave antennas.

To test its efficacy, two microstrip rectangular patch antennas were fabricated in the mechanical laboratory at INAOE using dimensions in Table I (section 3.1.2.1) and then, they were measured using a vector network analyzer from 20 GHz to 40GHz.

Figure 3.5, shows the final devices; though these antennas were fabricated by the same machine using a layout containing identical patches, wide differences were observed between both samples: the patch on Figure 3.5b is 19.8% bigger than the patch in Figure 3.5a; also, the feed line is different, the antenna in Figure 3.5b is wider than the antenna on Figure 3.5a meaning a lower

impedance is observed. These discrepancies with dimensions will affect the overall performance of these devices.

Figure 3.6 presents a comparison of the S11 parameters for both devices, as it is expected the resonance frequency of both devices is different (in the measurements a difference of 4GHz was observed). It is due to the size of the patch, the patch length is bigger in the antenna on Figure 3.5a than the one in Figure 3.5b (difference of 2.64 mm). Also, a high impedance mismatch is observed in both patches (only -11.6dB was measured), provided by the low accuracy in the lambda quarter transformer and feed line.



Figure 3.5 Final Devices After Milling Process (dimensions in mm)



Figure 3.6 Impedance Measurements for both patches

3.2.2 Chemical Etching Process

Chemical Etching Process consists of removing unwanted copper areas from copper clad substrates to recreate structures patterned in a layout file; this method relies on the action of a corrosive liquid that acts on unprotected areas to dissolve away the copper.

3.2.2.1 Toner transfer method

In this case, the layout is printed using a laser printer with ordinary toner (600 dpi is recommended) over an inkjet photo paper, this paper being coated with a thin wax-like layer on one side can easily transfer the pattern to a copper clad substrate. Theoretically, lines of one pixel in a 300dpi image should be possible (0.09mm), however, it depends on the layout and etching process, in general, it is harder to reproduce patterns where traces are too close. Figure 3.7 shows attempts to create coplanar waveguide (CPW) feed lines with a gap of 90 μ m, however in most cases the toner is too thin to protect the area, and the etchant removes copper in the whole area.



Figure 3.7 Attempts to reproduce coplanar waveguide lines

3.2.2.2 Photolithography

Photolithography is a microfabrication process that consists of transfering geometric patterns from a photomask using light, photoresist and chemical treatments on the copper clad substrate; therefore, the desired patterns are obtained after engraving the copper on the exposure patterns. This process is normally performed in a series of five steps: cleaning, masking, exposure and developing, etching and de-masking.

Figure 3.8 shows some examples using the photolithography process; in this case, the pattern was properly defined. Therefore, this technique will be used to develop the prototypes.



Figure 3.8 Examples of antennas fabricated using photolithography

3.3 Antenna in Package Technology (AiP)

The Antenna in package technology looks for solutions where the antenna is no longer a separate component within the wireless device, but it is integrated into the package. Materials and process technologies capable of realizing AiP in high volume for millimeter wave radio are limited, these approaches were summarized in section 2.4.1.

Despite the fact that materials presented in section 2.4.1 have excellent electrical properties their coefficient of thermal expansion are not well matched to silicon, cured PDMS exhibits a large coefficient of thermal expansion (CTE of about 310 ppm/°C); cured BCB has a CTE of about 60 ppm/°C; cured photoresist SU-8 2000 has a CTE 52 ppm/°C and cured Parylene has a CTE of 35 ppm/°C; these

coefficients are very different to the thermal coefficient in silicon wafers (CTE about 2.3ppm/.C); therefore, applications where the temperature changes, have the potential to suffer from structural damage.

Such mismatch in the coefficient of thermal expansion generates a stress at the interface of both materials, it leads to generate the force which delaminates off the primary layer from the silicon. Considering that stress-related cracking can be easily induced by sudden mechanical and thermal changes, DuPont polyimide PI2611 was proposed as a proper material for millimeter wave applications, It has a CTE of 3ppm/.C which is very close to the CTE of silicon (2.3ppm/.C) making it suitable as an interlayer in the development of antennas for in-package technology.

3.3.1 Polyimide PI2611

Polyimides are polymers extensively used in the electronic industry as dielectric and passivation layers in electronic devices, it displays excellent film properties such as low moisture, low stress (CTE = 3 ppm), high modulus of elasticity (8.5GPa) and a high resistance to chemical and solvents. This product is suitable for spin coating applications, it can be coated and patterned over a variety of substrates and metal surfaces, after application, the polyimide precursor is thermally cured into a fully aromatic polyimide film. The end product has ε_r = 2.9 and *Tan* δ = 0.002 @ 1 kHz [37].

3.3.1.1 Characteristics of PI2611-Layer

In order to determine different variables in the fabrication process such as spinner speed, curing times, and the number of coatings; samples over corning glasses and over silicon wafers were used. Test structures were developed for each case, and finally measurements using a profilometer (force: 2mg; resolution 0.5µm) allowed analysis of the degree of planarity, thickness and repeatability of one coating.

Corning Glass Samples

Figure 3.9 shows a summary of the process to develop one polyimide layer, basically, it is necessary to cover about 70% of the sample, spread it using a spinner at the desirable speed, and cure it using a convection oven. In this case 1500 rpm was used, this speed was obtained after some tests coating polyimide at 500 rpm, 1000 rpm and 1500 rpm, for slow coatings the polyimide layer were too thick to be cured properly and then bubbles were observed on the surface. Once the polyimide is cured, it shows high resistance to chemicals and solvents, therefore, dry etching is required to create the pattern.

Structures from Figure 3.9c were measured using a profilometer, Figure 3.10 shows the curves obtained for different points and samples, good film properties are observed, the samples presents high planarity and low roughness and also the process is repeatable, no wide variations are observed between different samples.



Figure 3.9 Procedure to Develop Test Structures over Corning Glass



Figure 3.10 Profilometer Measurements (force: 2mg; resolution 0.5µm)

Silicon Wafer Samples

Considering that the form of the sample may change the thickness of the polyimide layer, further test structures were fabricated; in this case, a mask containing structures with dimensions in the micrometer scale was used.

Figure 3.11 illustrates the basic steps followed to make the structures: First, the wafer is cleaned and isolated with a layer of SiO₂. Second, a metal layer of aluminum is added to shield and stop the dry etching (Figure 3.11a). Third, the polyimide is applied and cured following the same process as in corning glasses. Four, once polyimide has been cured another layer of aluminum is added (Figure 3.11d). Five, photolithography is used to create the patterns: photoresist is revealed and developed (Figure 3.11f), and wet etching is used to define the structures (Figure 3.11g). Six, exposed polyimide is removed by dry etching; the end structure is showed in Figure 3.11h.

Using a profilometer the end structures were measured, the main concern was the final thickness, therefore, multiple measurements were done in order to examine this variable. As shown in Figure 3.12, the polyimide film is pretty stable, a layer of 11.6 μ m was obtained, the process is replicable to other substrates without major changes and high planarity is obtained.



Figure 3.11 Procedure to Develop Test Structures over Silicon Wafers



Figure 3.12 Profilometer Measurements (force: 2mg; resolution 0.5µm)

3.3.2 Antennas Fabrication Process

Once the process to coat and cure polyimide films was properly defined, the process to fabricate the antenna was established. This process is divided into a series of steps, detailed below.

The first step was to prepare the substrate for the deposited film. In this case, a proper cleansing of the wafer was performed before a 0.5μ m SiO2 layer was obtained by thermal oxidation. Once the isolation layer was ready, a metal layer of aluminum was deposited to shield the antenna from electromagnetic interference. Finally, an oxygen plasma etch was used to promote adhesion.

The second step was the deposition of the isolation film; in this case PI2611, a polymer was applied using spin coating technology, for which a 10 μ m layer was obtained at 1,500 rpm on one application, but this process can be repeated to obtain the desired thickness. For this work, a 60 μ m layer was formed by multiple coatings and curing of the films (see Figure 3.13c).

The third step was to define the correct antenna pattern; therefore, a mask was made on INAOE's microelectronic laboratory with one reduction (1:20.3) to define its geometry, the transfer was made with a common lithography process and wet etching of the aluminum (see Figure 3.13e-g).

Figure 3.13h shows a close view of the final structures, these structures were effectively transferred to the aluminum layer, the borders present high definition for different geometries, also from the pictures taken on the microscopy (Figure 3.13f) the photoresist was completely removed, even in the critical parts like in the coplanar waveguide, in this case, the line is well defined.

(a) Wafer +SiO2+Al	(b) One coat of PI2611	(c) Six coats of PI2611
(d)Top Metal Layer	(e)Photoresist Patterning	(f) Result after Al-etch
(g) End Devices	(h) Close	se View

Figure 3.13 Antennas Fabrication Process

3.4 Chapter Review

In this chapter, different technological approaches for the development of millimeter wave antennas were explored. First, silicon micromachining was evaluated, full-wave simulations analyzing which may be the actual size of the cavity gives clues of how sensitive the device is to this variable, resonant waves inside the cavity may even change the radiated pattern, then bigger cavities are advised, but it makes this solution not feasible in a real case because size and cost are usually restricted.

Also, different fabrication methods for the development of PCB trace antennas over Rogers 4003C were studied, from the measurements and tests done for millimeter-wave antennas, it is necessary to use traditional photolithography to obtain well-defined structures. For Antenna in Package approach, polyimide PI2611 was chosen, this material was then evaluated and characterized using different test structures, the results shows that this film has excellent features and can be employed to fabricate antennas directly on to a silicon wafer. Finally, the procedure to fabricate the antennas of this dissertation was detailed.

Chapter 4

THE ANTENNA'S IMPEDANCE MEASUREMENTS: MATCHING NETWORK APPROACH

4.1 Antenna's Impedance Measurement

The Antenna's impedance measurements are typically done with network analyzers; these equipments accurately measure the incident, reflected, and transmitted energy. Usually, a transmission line is employed to feed the device under test (DUT); the network analyzer measures the energy that is reflected back down the transmission line towards the source (b₁) and the energy successfully transmitted to DUT (a₁), with this data the S_{11} parameter is obtained.

Vector Network analyzers measure the incident and reflected waves directly during a frequency sweep (represented by f_0 and f_1 in Figure 4.1), the amplitude and phase information in these waves makes it possible to quantify the reflection and transmission characteristics of a DUT. The results are commonly

displayed in S-Parameters. Figure 4.1, illustrates these process for one port measurements.



Figure 4.1 One Port Measurements

4.1.1 S₁₁ Parameter

The S₁₁ parameter represents how much power is reflected from DUT, regarding antennas if $S_{11} = 0 \, dB$, then all the power is reflected from the antenna and nothing is radiated, if $S_{11} = -\infty \, dB$, then all the power is delivered to the antenna, typically -10dBs are enough to assume that the antenna is radiating, however, the accepted power is either radiated or absorbed as losses within the antenna, then it depends on the application. The antenna's bandwidth, resonant frequency, and impedance can be obtained doing a frequency sweep for S_{11} parameter.

4.1.2 RF - Probes

The connector is an important part in the measurement of microwave circuits since a perfectly matched condition must exist at a connection between two devices for maximum power transfer into a load. The need for efficient power transfer is one of the main reasons for the use of special connectors at high frequencies, Reed Gleason and Eric Strid invented the first high-frequency wafer probes in 1980, these devices allow testing of Monolithic microwave integrated circuit (MMIC) devices on the wafer without mounting them or wire bonding them. There are different types of probes; however, ground–signal-ground is the most common type of RF-probe [38]. One important feature of the RF-probes is the distance between center to center of the probe tip (probe pitch); for millimeter-wave frequencies, it is limited to hundreds of microns, typical values are 100, 150 and 250 microns. In this dissertation a GSG RF-probe of 150 μ m pitch is employed to characterize the antennas (This is shown in Figure 4.2).



(a) VNA + RF-PROBES

Figure 4.2 Equipment Employed to Antenna's Impedance Measurement; (a) Tech bench. (b) Probes Top view. (c) GSG RF-probe

4.2 Proposed Method

There are, however, different challenges regarding the measurement of microwave antennas, especially those related with the pads used to access the device. In general, the use of pad structures (Figure 4.3a) introduces parasitic effects that impact the S-parameter measurements of the antenna. As was described in chapter 2, de-embedding techniques have been proposed in order to extract the effect of pads in S-parameter measurements; however, these

methods involve additional structures, occupying more chip area and requiring additional data post-processing.

In this dissertation, a tunable matching network is proposed to measure planar antennas (Figure 4.3b). The method is used to measure antennas fabricated on wafer and on PCB technology without the need for additional test fixtures. The proposed method shows an excellent agreement with numerical electromagnetic simulations and the antenna measurements.



Figure 4.3 Measurement Approaches. (a) Schematic measuring process used in planar antennas. (b) Embedded matching network, notice only one transmission line is used to access to device.

4.2.1 Theory

At high frequency transmission lines can be used to reproduce the same operation as that of lumped elements; thereby terminating them in short or open circuits it is possible to develop a completely passive network with simple conductors. Figure 4.3b illustrates this network: at the feed point, the system will see two transmission lines with characteristic admittance Y_0 and propagation constant γ (α +j β); one of them is short-circuited and the other one feeds the antenna. The input admittance of the system at the feed point is obtained by transforming the edge admittances to the feed point.

Following the nomenclature in Figure 4.3b, and considering the use of low-loss substrates a lossless transmission line will be assumed, the resulting expression, from the equivalent circuit of Figure 4.3b, is obtained as,

$$Y_{T} = Y_{0} \left(\frac{Y_{0} + jY_{A}\tan(\beta L_{2})}{Y_{A} + jY_{0}\tan(\beta L_{2})} - jCot(\beta L_{1}) \right)$$
(4.1)

Where Y_A and Y_0 are the admittance of antenna and transmission line respectively. To match the antenna, the admittance of the probes ($Y_{ref} = 1/50 + j0$) must be equal to the input impedance of the system, or:

$$\frac{1}{50} + j0 = Y_1$$

Separating into real and imaginary parts (Eq. (4.2) and (4.4)), the final dimensions of the matching network can be obtained.

$$\frac{1}{50} = Y_0^2 Y_A \left(\frac{1 + \tan(\beta L_2)^2}{Y_A^2 + Y_0^2 \tan(\beta L_2)^2} \right)$$
(4.2)

This yield to,

$$L_{2} = \frac{1}{\beta} \cdot atan\left(\sqrt{\frac{50Y_{A}^{2} - Y_{0}^{2}Y_{A}}{Y_{o}(Y_{o}Y_{A} - 50Y_{o})}}\right)$$
(4.3)

$$0 = Y_0 \left(\frac{(Y_A^2 - Y_0^2) \tan(\beta L_2)}{Y_A^2 + Y_0^2 \tan(\beta L_2)^2} - \cot(\beta L_1) \right)$$
(4.4)

Finally, L_1 is obtained combining Eqns. (4.2) and (4.4).

$$L_{1} = \frac{1}{\beta} \cdot acot \left(\frac{Y_{A}^{2} \tan(\beta L_{2}) - Y_{o}^{2} \tan(\beta L_{2})}{Y_{A}^{2} + Y_{o}^{2} \tan^{2}(\beta L_{2})} \right)$$
(4.5)

4.2.2 Designing Matching Impedance Networks for PCB and On-Chip Coplanar Antennas

This section contains two examples (Figure 4.4) illustrating how the configuration on Figure 4.3b can be used to effectively measure antennas. First, Antenna's features such as dimensions and impedance are determined, and then the data is used to define the length of the matching network, employing equations (4.3) and (4.5).



Figure 4.4 Photograph of Antennas used for Validation, (a) over Rogers 4003C and (b) over Polyimide-Si Substrate. All antennas dimensions are in millimeters.

4.2.2.1 Antenna on PCB technology

In Figure 4.4a, the antenna fabricated on Rogers 4003C is presented, this antenna is a triangular slot designed to operate at a resonant frequency (f_r) of 35 GHz, on a low-loss substrate (ROGERS 4003C) whose loss tangent is 0.0027 and relative permittivity is 3.55.

From [39]; this kind of antenna can be seen as a dipole with the aperture's width responsible for resonance. Choosing the first propagation mode ($x \approx \lambda/4$) yields:

$$f_r = \frac{c}{4(x - 2\Delta x)\sqrt{\epsilon_r}} \tag{4.6}$$

Where *c* is the speed of light in free space, ϵ_r is the dielectric constant of the region surrounding the transmission line, and Δx accounts for the fringing field effect. Replacing design variables in Eq.(4.6) x = 1.4 mm. In order to improve impedance matching across the operating band, following the recommendation on [39] the flare angle should be 45°, and then y = 1.65 mm.

The matching network is designed based on antenna and transmission line admittances (Y_A , Y_o), where the transmission line dimensions were designed to ensure $Y_o = 1/50$ using the expressions in [40]. Y_A is calculated considering that the input impedance of a slot antenna ($Z_A = 1/Y_A$) can be estimated in terms of its complementary dipole, Z_d ; whereas the impedance of the equivalent triangular patch antenna can be obtained through Schelkunoff approximation [41]. Combining both equations yields:

$$Z_A = \frac{\pi Z_{int}}{4\ln\left(\cot\left(\frac{\theta_h}{2}\right)\right)} = \frac{376.7\pi}{4\sqrt{\varepsilon_{eff}}\ln\left(\cot\left(\frac{\theta_h}{2}\right)\right)}$$
(4.7)

The effective permittivity in the line is $\varepsilon_{eff} = 1.96$. It is calculated from design equations for coplanar waveguides [40] and known parameters ($f_r = 35GHz$ and copper thickness $t = 20\mu m$.). Using Eq. (4.7), $Z_A = 355\Omega$ and $Y_A = 0.0028 S$.

Finally, L_1 and L_2 are estimated using Eqns. (4.3) and (4.5). Notice that they are periodic; there are multiple solutions each time $\beta L_2 = \pi$. In this case, three roots are available, and the following values were chosen:

$$L_1 = 0.41mm;$$
 $L_2 = 2.7mm$

4.2.2.2 Antenna on Wafer-PI2611 Substrate (60GHz)

In Figure 4.2b, the antenna fabricated with CMOS technology is presented; the design was proposed to be implemented on a low resistivity silicon wafer of 300µm thickness (common substrate on CMOS technology). First, the surface of the wafer was isolated using a thin layer of SiO2 (0.8µm), upon which and a metal layer (Al 0.5µm thickness) was deposited. This was followed by a 60µm layer of PI2611 ($\varepsilon_r = 2.9$ and $tan\delta = 0.002$), which serves as the antenna's substrate, and finally a top metal layer of aluminum was deposited. The patch, of width (W) and length (L), was fabricated on this layer.

For this antenna, the resonance frequency is mainly determined by the length of its patch (x) [42], then:

$$f_r = \frac{c}{2(x + 2\Delta x)\sqrt{\epsilon_r}} \tag{4.8}$$

From Eq. (4.8) and considering a high fringing field effect ($\Delta x = 0.2$) produced mainly by its geometry (S = 0.2mm), the following dimensions were estimated: x = 1.15 mm and y = 1.4 mm.

Once the admittance of the network elements is known (Y_A , Y_o), the dimensions of the matching network can be estimated. First, the feed line was designed to have an admittance of $Y_o = 0.02 S$. Then, the antenna's admittance Y_A was estimated from the cavity model for rectangular patches [43], and was found to be $Y_A = 30.0027 S$. Finally, L_1 and L_2 were estimated using Eqns. (4.3) and (4.5). Due to the periodicity of these equations multiple solutions are available, but the following values were chosen considering they were reasonable and implementable on the design.

$$L_1 = 0.18mm;$$
 $L_2 = 2.77mm$

4.2.3 Measurements and Results

Once established the dimensions of the antenna and matching network, the devices were fabricated using the micro-fabrication process described in chapter 3, the dimensions and materials are illustrated in Figure 4.2. Therefore, the structures are ready to be measured. One port S-parameter measurements using 150 μ m pitch RF-probes were performed on both antennas. By placing the probes at the design length (L₁) the performance of the antenna was evaluated.

4.2.3.1 S-Parameter Analysis

The antennas were measured at points close to their design values. For PCBtechnology, the probe was placed at $L_1 = 0.4$ mm and for On-Wafer approach, it was placed at $L_1 = 0.26$ mm. In Figure 4.5, the reflection coefficient for both cases is illustrated. The observed resonant frequencies correspond to the excitation of different modes in the devices when the resonance condition is achieved. For the PCB example only the first resonance mode is excited (Figure 4.5a); however, for the on-chip example two resonant modes are excited (Figure 4.5b).

Figure 4.5 shows a comparison between one port measurements done over the prototypes, the circuital model of figure 4.3 and the simulation results; note that no further de-embedding methods were required to obtain excellent agreement between experimental data, full wave simulations and the transmission line model described in section 3. Finally, the attenuation at resonant frequency is close to -40dB, meaning an excellent matching was accomplished, validating the effectiveness of this method for millimeter wave applications.



Figure 4.5 Results for direct measurements of (a) On-Rogers and (b) On-Wafer examples. Experimental results are compared with simulations and the proposed models (eq. 2).

4.3 Chapter Review

This chapter presents an overview of the basic concepts and elements necessary to measure antennas at millimeter wave frequencies. The measurement process followed in this thesis was discussed; this novel technique employs only a matching network to measure millimeter wave coplanar antennas. The embedded matching network has been presented and validated with two examples; a 35GHz antenna fabricated on PCB technology and a 60GHz coplanar antenna on a silicon wafer (fabrication details were discussed on chapter 3). Excellent agreement between experimental data, full wave simulations and the transmission line model illustrates the validity of this approach. This proposal results in a practical way to measure millimeter CPW antennas when RF-probes are needed.

Chapter 5

CIRCULAR POLARIZATION IN COPLANAR PATCH ANTENNAS

5.1 Antenna Polarization

The polarization of an antenna is the spatial variation of the electric and magnetic field as time progress (i.e. polarization of the wave radiated) in a given direction by the antenna when transmitting. Each antenna has a characteristic polarization, for example: coplanar antennas present linear polarization and helix antennas produce circularly polarized waves. In linearly polarized antennas, the electric field at a fixed point on the patch oscillates back and forth along a vertical or horizontal line; and in the case of circularly polarized antennas, the electric field remains constant in magnitude but rotates describing a circular path; Figure 5.1 illustrate this polarization states [44].



Figure 5.1 Some Antenna's Polarization States: (a) Circular; (b) Linear

5.1.1 Inducing Circular Polarization

Circular polarization can be induced in planar antennas by multi-feed arrangements or by single-feed techniques where slight modifications made to the antenna's elements induce orthogonal electric fields, some of these works were summarized in Chapter 2.

In the following section, a single feeding approach to produce circular polarization in coplanar patch antennas is showed. First, an overview of the antenna is presented, this antenna was chosen because its fabrication is easy and its operating principle is well-known. Then, simulations using a full-wave field solver were employed to study the impact of modifications in the point of feeding and ground plane, these elements were the key to induce circular polarization in these antennas, the design was done at high frequencies in order to examine its performance as a solution for AiP technologies.

5.2 Coplanar Patch Antennas (CPA)

The coplanar patch antenna was first introduced by J. W. Greiser in 1976, it was originally considered as a loop antenna, but further studies [45, 42] showed that this device behaves more like a monopole patch antenna than a loop antenna. In Figure 5.2 a basic CPA antenna is presented, like any regular rectangular patch antenna, the lowest resonant frequency of this antenna is determined by the patch length (L) and it is about half guided wavelength [35].



Figure 5.2 Elements of a Coplanar Patch Antenna

5.2.1 CPA for AiP Technology

As was detailed in chapter 2, to ensure a proper integration with silicon, a polyimide layer with a dielectric constant of $2.9 \sim 3.3$ will be used as the substrate of the CPA. The polyimide was chosen because it has excellent mechanical and chemical properties, it is lightweight, flexible, and resistant to heat and chemicals. The end devices are presented in Figure 5.3.



Figure 5.3 CPA for Antenna in Package Technology

5.2.2 Antenna's Design

In this section the dimensions of the patch and feeding network is defined.

5.2.2.1 Patch Dimensions

Patch geometry is mainly determined by the operating frequency and the dominant propagation mode (most cases it is TM010 [12, 14]); the resonant frequencies is obtained from eq. (5.1).

$$(f_r)_{010} = \frac{c}{2(L+2\Delta L)\sqrt{\epsilon_r}}$$
(5.1)

Where *c* is the speed of light in free space, ϵ_r is the effective dielectric constant of the region surrounding the transmission line, and ΔL indicates the fringing field effect.

5.2.2.2 Feeding

The CPW feed line was designed to have an input impedance of 50 ohm in order to match the measurement system. The line-width (*s*) is 50 μ m, and the gap-width (*g*) is 90 μ m. These dimensions were estimated by the close-form formulas given in [46] and optimized by simulations.

5.3 Proposed configuration to achieve Circular Polarization in CPAs

To achieve circular polarization by a single-feed approach, an asymmetric feeding is proposed in this thesis; in order to create a perturbation in the electromagnetic field that change the polarization. The proposed device is presented in Figure 5.4.



Figure 5.4 Circularly Polarized CPA

5.3.1 Dual Band Operation

When circular polarization is induced, two modes with the same amplitude and different phase (90° apart) are excited. In the case of a rectangular patch dominant modes are TM_{010} and TM_{001} , Therefore, is possible create a device with dual-band operation employing a simple patch. In this case, L and W determine the resonant frequencies of this device.

In order to illustrate this property, a parametric study using HFSS, software for 3D full-wave electromagnetic field simulation, was done. The three cases simulated are presented in the following sections.

5.3.1.1 Simulations

Using eq. (5.1) a rough estimation of the antenna's geometry is obtained. As was established before, each dimension is responsible for radiation when circular polarization is induced in a CPA. For 60GHz operation L=1.05 and W will be 1.4 mm; Then replacing on eq. (5.1) yields to the next resonant frequencies,

$$(f_r)_{010} = \frac{3 \cdot 10^8}{2 \cdot (1.05 + 0.4) \cdot 10^{-3} \sqrt{2.9}} = 60.7 GHz$$

$$(f_r)_{001} = \frac{3 \cdot 10^8}{2 \cdot (1.4 + 0.4) \cdot 10^{-3} \sqrt{2.9}} = 48.9 GHz$$

Once preliminary dimensions were established a 3D representation of the antenna was built on HFSS and then the value for L was tuned. Figure 5.5, shows the reflected power for three different patch dimensions.



Figure 5.5 Reflected Power in Circularly Polarized CPA Antenna
5.3.2 Elements Responsible of CPA Circular Polarization

The elements responsible for circular polarization can be determined by a comparison study of the effect of the different elements in the reflected power. Two cases were evaluated:

5.3.2.1 Shield Metal Layer Influence

Taking into account that the proposed antenna was designed over a wide layer of a low resistivity substrate (100Ω -m for Silicon was assumed), if the metal shielding the antenna were removed, the electromagnetic behavior of the device may change and then there is no point in conducting this test.

Therefore, the silicon layer is omitted in this simulation. Figure 5.6, shows the reflected coefficient for two coplanar patch antennas with the same geometry, but different feeding points. To sum up, a symmetric and asymmetric feeding are simulated but in both cases the back-ground conductor is eliminated.



Figure 5.6 Antenna's Reflected Power for a device with and without a back metal layer.

5.3.2.2 Symmetric and Asymmetric Feeding

In this case, the size of the patch is constant (L = 1.15 mm and W = 1.4 mm) and was only analyzed the change in the position of the feeding. Two cases were considered: when the feeding is located in the low left corner as was proposed in Figure 5.4, and when it is located in the middle (Figure 5.3). Finally, simulations of the reflected power in the frequency range of 0GHz – 67GHz were presented (Figure 5.7).



Figure 5.7 Antenna's Reflected Power for symmetric and asymmetric feeding

5.3.3 Discussion

The simulation results suggest that circular polarization can be used to enhance the properties of CPA antennas; in this work, a dual band operation was obtained from a traditional rectangular patch. Figure 5.5 shows that each dimension controls one resonant frequency; for example, when the patch length is 1.15mm, the frequency calculated from Eq. (5.1) is 60.7GHz, which is a rough estimation of the results of the simulation (61.2GHz for this condition). Furthermore, when only the dimensions of the patch were interchanged (W changes from 1.15mm to 1.4mm and vice versa) the resonant frequencies were almost the same (54.2GHz and 61.2GHz ~ 61.6GHz). One interesting property is that circular polarization is achieved in CPA antennas by the influence of the back metal layer and the asymmetric feeding. Figure 5.6 and Figure 5.7 illustrate this behavior; in both cases when this feature is removed (the back conductor in Figure 5.6 and the asymmetric feeding in Figure 5.7) the dual band operation disappears (There is only one resonant frequency around 60GHz instead of two).

5.4 Measurements of Circularly Polarized CPA Antennas

In order to validate the simulation results, a coplanar patch antenna with symmetric and asymmetric feeding was fabricated and measured following the procedure described in chapters 3 and 4. Figure 5.8 shows the devices under test.

The manufactured antennas are identical (i.e. both have a patch length of 1.15 mm and a width of 1.4 mm), the same case evaluated in section 5.3.2.2, therefore this is a test to validate the idea that dual-band operation in coplanar antennas can be produced by inducing circular polarization in coplanar patch antennas.



Figure 5.8 Coplanar Patch Antennas: (a) symmetric (b) asymmetric feeding



Figure 5.9 Experimental Results



Figure 5.10 Comparison between simulation and measurements

5.4.2 Discussion

Figure 5.9 shows the radiated power in both cases, when the antenna has a centered feeding, only one resonant frequency is observed but if the feeding point is moved from the center to left corner, two resonant frequencies are observed. It validates the proposal presented in this thesis, and as was expected; at 60GHz circular polarization, this induces orthogonal modes that produce dual-band operation.

Finally, the accuracy of 3D electromagnetic field solver was evaluated; it is illustrated in Figure 5.10. Measurement data was compared with simulation results for both antennas. In the case of a traditional CPA antenna, the data seems to have good correlation; however when circular polarization is induced, the software fails on estimates the resonant frequency of the device for about 2.5GHz. It indicates that it is difficult to account the complete effect of circular polarization.

5.5 Chapter Review

In this chapter basic concepts of polarization were introduced, they give an idea of the necessary steps to produce circular polarization in normal patches, the different approaches propose complex solutions, the method presented here to induce circular polarization is effective and doesn't require more devices (i.e. extra feeding networks). Once circular polarization is achieved, a dual-band device is proposed by implementing a rectangular patch instead of a square patch as it is normally done, this solution only requires a change in patch length and width to control the resonant frequencies of the system. The proposal was first studied using full wave simulations and then two prototypes were fabricated, the effect of circular polarization was observed when the feeding of CPA is changed and two resonant frequencies were measured instead of one. Then this solution does not require additional space and produces a dual-band device useful in applications highly selective in frequency like RFID tags.

Chapter 6 CONCLUSIONS AND FUTURE WORK

6.1 Contributions

Migration of wireless systems to millimeter wave frequencies requires cost reduction solutions that take advantage of the compact size, high bandwidth and extreme data rates that a high frequency operation offers. New materials with better mechanical, thermal and electrical properties are now available; fabrication processes have reached nanometric resolutions and depending on the antenna's type, different properties can be enhanced. Multiple applications had been created around this technology, internet of things, imaging technology, biomedical applications and interferometry radars base its operation in this technology.

Throughout this dissertation, the challenges in design, fabrication and measurement at millimeter-wave frequencies were examined; the analyses included the review of previous works, full-wave simulations, and hands-on tests that allowed judging the common approaches employed to fabricate and measure antennas at lower operating frequencies, such as the ones used in current WLAN or WPAN applications. The work presented in this dissertation draws the following conclusions and contributions:

- Even though silicon micromachining has been used to tailor an antenna's electrical features, the process is highly sensitive to variations, and can give characteristics that substantially deviate from the targeted ones. A precise control of cavity size is needed, for instance, since this factor determines resonant frequency, impedance, and radiation pattern.
- Antenna in Package technologies are becoming fundamental in the development of millimeter wave antennas since better materials are continually being developed; for example, PI2611 shows good film properties, such as adhesion to many materials, chemical stability and a CTE closer to that of silicon, and a reduced loss tangent. This work demonstrated the feasibility of using multilayered polyimide films to serve as the substrate for an antenna, thus being able to integrate it in a traditional CMOS process.
- PCB trace antennas are also an attractive option for the development of millimeter wave antennas since good quality substrates at reasonable costs are available, such as Rogers 4003C. The development of millimeter wave antennas for this technology, however, is limited by the fabrication process since the standard methods (i.e. photolithography) fail to produce structures with sufficient reliability.
- As was described in Chapter 2, the current methods used to measure antennas require the use of test fixtures to access DUT. These test fixtures have a transfer function in the bandwidth of the measurement, and therefore have to be de-embedded from the measured DUT data. From previous works

related to the antenna's measurements; de-embedding methods and test fixtures are not always the same, there is no unified technique or methodology, and each work proposes different structures and techniques which impact the accuracy of the measurements. Finally, most of them do not mention the feeding line design, which they assume to be of arbitrary length.

- Conversely, the embedded matching network herein presented and validated with two examples in Chapter 4 (a 35GHz antenna fabricated on PCB technology and a 60GHz coplanar antenna on a silicon wafer) shows an outstanding matching. The measurements have an excellent correlation with full wave simulations and the developed transmission line model. This proposal results in a practical way to measure millimeter wave CPW antennas when RF-probes are needed. It simplifies the design and the S-parameter extraction because only a transmission line is required to measure the antenna (DUT).
- In Chapter 5, a single-layer, single-feed, dual-band antenna developed for highly integrated 60GHz radios have been presented; this device is the result of combining a rectangular CPA patch and an asymmetric feeding line. The simulation and measurement results show that it is the attained circular polarization which produces a dual-band device, useful for applications which require high frequency selectivity, such as RFID tags.

6.2 Future Work

Regarding the development of millimeter wave antennas; the fabrication process presented in this dissertation for AiP technology (polyimide coatings) can be used to produce more complex designs that cope with the pitfalls of transmission by planar antennas, such as low gain. Furthermore, polyimide coating can be used to produce other types of antennas, such as dielectric rods or microwave slot waveguide antennas.

The measurement method proposed in this dissertation is applicable to any CPW-fed planar antenna, however it hadn't been used to measure antenna arrays, which is a set of two or more antennas that combine their features to achieve an improved performance. Therefore, the next step would be to use this approach to characterize antenna arrays.

Due to the advantages of having a dual band device with a single patch, as is the case of the antenna proposed in Chapter 5, this circularly polarized CPA antenna could be used as a building block for an array used in RFID tags.

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