Design and Simulation of Compact Dual Frequency Antenna in Multilayer GaAs MMIC Technology with Coplanar Waveguide Feeding

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<tr>
<td>MSA</td>
<td>Microstrip Antenna.</td>
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<tr>
<td>MIC</td>
<td>Microwave Integrated Circuit.</td>
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<tr>
<td>MMIC</td>
<td>Monolithic Microwave Integrated Circuit.</td>
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<tr>
<td>DFA</td>
<td>Dual Frequency Antenna.</td>
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<tr>
<td>GaAs</td>
<td>Gallium Arsenide.</td>
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<tr>
<td>CPW</td>
<td>Coplanar Waveguide.</td>
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<tr>
<td>EM</td>
<td>Electromagnetic.</td>
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<td>BW</td>
<td>Bandwidth.</td>
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<td>TL</td>
<td>Transmission Line</td>
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<td>MoM</td>
<td>Method of Moments</td>
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<td>VSWR</td>
<td>Voltage Standing Wave Ratio</td>
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ABSTRACT

This project addresses the analytical design and simulation of two types of millimetre wave antennas: a single patch antenna and a dual frequency antenna. Both antennas are based in the GaAs MMIC multilayer technology and use a coplanar waveguide (CPW) feeding. The analytical design is based in the transmission line (TL) model for microstrip antennas. The simulations are conducted in the 3D electromagnetic (EM) simulator Momentum, which is based in the Method of Moments (MoM). The proposed dual frequency antenna is based in the premise of dividing a microstrip patch in several multiresonators, producing two resonant frequencies by EM parasitic coupling. This particular structure has not been used to provide dual frequency operation in the millimetre wave range, specially combining GaAs MMIC multilayer technology with CPW feeding. A detailed design procedure is developed for the single patch antenna, such that it can be used as a guide for future designs. A parametric study of the single patch antenna is performed to understand the influence of various parameters in the antenna operation. The complete design process led to the successful development of a single patch antenna that works around 35 GHz and a dual frequency antenna that works around 35-50 GHz. Results showed that the combination of GaAs MMICs with CPW feeding can produce efficient antenna designs regarding size considerations. Momentum was successfully used to optimize both antennas with respect to size, resonant frequencies, return loss and input impedance.
DECLARATION

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DEDICATION

To Janneth, Camila, Italo and Sofía; for their unconditional love and support.

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CHAPTER 1: INTRODUCTION AND RESEARCH OBJECTIVES

1.1 Introduction

The great developments in communication systems and semiconductor technologies during the past few decades have created the need for highly compact and efficient antennas. Modern communication applications require small size antennas with suitable performance characteristics. Microstrip Antennas (MSA) have proved to be an outstanding alternative for modern communication systems due to their great advantages, in comparison to other compact antenna technologies. MSAs feature interesting characteristics including low volume, thin profile, ease of fabrication and compatibility with monolithic microwave integrated circuits (MMIC) [1]-[7].

MSAs have found applications in all kinds of fields such as radar systems, satellite communications, mobile radio and even biomedical systems [1], [2]. In the present, a great number of these applications require antennas that could provide dual frequency operation. Dual-frequency compact antennas are required because they can cover two different frequency bands without the need of an extra device; thus reducing size, weight and cost in communication systems [7]-[12].

Dual frequency antennas (DFA) have attracted the interest of industry and researchers; consequently, a countless number of configurations and designs have been proposed around the world. In addition, the great versatility of MSAs and the requirements of modern systems motivated the combination of different design techniques and technologies [7]-[12]. Past works have shown that the use of multilayer MMICs combined with efficient feeding networks, such as a Coplanar Waveguide (CPW), can produce antennas with suitable size and performance. As a consequence the use of GaAs MMIC technology and CPW for the design of DFAs is a very attractive alternative [9], [13]-[15].

This project is intended to design and simulate a compact antenna to provide dual frequency operation, based in the MMIC multilayer technology with CPW feeding. During this work the whole antenna development will follow two steps. First, an antenna design will be addressed, based in theoretical descriptions and models. Second, the designed antenna will be simulated using the 3D Electromagnetic (EM) planar simulator Momentum.
1.2 Dual Frequency Antenna Characteristics

Dual frequency operation can be achieved by diverse design variations, such as multilayer structures, parasitic elements, the use of shorting pins or diodes, reactive loading techniques and slotted radiating elements [7]-[10], [13], [14]. However, most these design techniques present two main limitations: size is significantly increased in comparison to single frequency antennas and the addition of devices like diodes is difficult in high frequencies [7], [8], [10].

Those limitations are the main reason to propose an alternative technique in this work. It is desired to use a design based in the division of a conventional rectangular microstrip patch, into smaller elements and produce a multiresonator structure with the same overall planar dimensions as the original rectangular patch. The design scheme is depicted in Figure 1, where a single patch and the proposed antenna are compared [5], [7], [16]-[19]. This kind of structure was conceived in principle to increase the bandwidth (BW) of MSAs, with excellent results reported in the works of Aanandan et al [17]-[19].

![Figure 1: (a) Single patch antenna (b) Multiresonator structure [5], [7], [16]-[19].](image)

It has been proved that the structure in Figure 1 is able to produce a BW which can be 10 times the BW of a single patch antenna, without increasing its area [7], [16]-[19]. This antenna has not been extensively explored and a clear theoretical description of its behaviour has not been introduced yet [7], [16]. Furthermore, the use of this structure as a DFA, combining multilayer GaAs MMIC technology and CPW feeding, has not been reported either.

In this project the structure of Figure 1 is going to be explored to design a DFA to operate around 35-50 GHz. This specific frequency range is chosen because there is increasing interest in satellite, radar and even new WLAN applications around this band. In addition, the
dimensions of an antenna operating around 35-50 GHz area will not exceed a few millimetres; which is desirable for modern communication systems [9], [20]-[24].

1.3 Aim and objectives

The main aim of this work is to design and perform software simulations of a compact microstrip antenna to effectively provide dual frequency operation.

From the aim of this project, several specific objectives are derived and are listed as follows:

i) Design analytically a single patch microstrip antenna (MSA), based on the multilayer GaAs MMIC technology with CPW feeding, to work around 35 GHz.

ii) Describe in detail the design process of the single patch MSA and establish a design guide that can be used on antennas with similar characteristics.

iii) Use the analytical criteria of the single patch MSA to develop a dual frequency antenna (DFA), based in a multiresonator structure, to work around 35-50 GHz.

iv) Simulate both antennas in the 3D EM simulator Momentum and compare results with analytical designs.

v) Analyse the implications and advantages of using a GaAs MMICs and CPW.

vi) Conduct an optimization of the single patch antenna in Momentum, in order to achieve suitable operation with respect to: resonant frequency, return loss and input impedance.

viii) Perform a parametric study of the dual frequency antenna to establish a design guide and optimize its size and performance.
CHAPTER 2: BACKGROUND THEORY AND LITERATURE REVIEW

MSA were first proposed back in the 1950s and started to be extensively studied from the 1970s. Since then, several methods of analysis were developed in order to explain their operation [1]-[7]. In the case of dual frequency antennas (DFAs), a great number of models have been applied for their design and analysis [7]-[12]. This chapter pretends to summarize the most relevant theoretical definitions concerning the antennas developed in this project: a single patch antenna and a multiresonator DFA, both in GaAs technology with CPW feeding. The chapter will be divided in two main sections: background theory for antenna design and a literature review of previous works relevant to DFAs.

2.1 Background theory for antenna design

2.1.1 Basic notions of Microstrip Antennas (MSAs)

The basic structure of a MSA consists of a thin metallic strip, commonly called patch, placed above a dielectric substrate and a ground plane. Figure 2 presents this basic configuration, where the microstrip patch is the radiating element. Regular shapes are usually chosen to simplify the patch analysis and the most widely employed are rectangular and circular [1]-[7]. MSAs are commonly fed by a coaxial probe or a coplanar microstrip line. However, in the present many other alternative feeding techniques are used [1]-[7].

When a voltage is driven into a MSA through the feeding network, surface currents are excited in the patch and fringe electric fields are produced [2]. The patch presents radiating and not radiating slots depending on the feeding technique and antenna dimensions. In general patch antennas are designed such that radiation is produced along the direction of the patch length. The patch resonates when its length is close to \( \lambda/2 \) [1]-[6].

Many substrate materials have been developed to be used in MSAs, given that substrate characteristics are determinant for antenna behaviour. Usually thick substrates with low dielectric permittivity produce antennas with good performance, because fringe fields are enhanced [1]-[3], [6], [7]. The disadvantage of thick substrates is larger antenna size. On the other hand, thin substrates with lower dielectric permittivity produce less efficient antennas; but reduce size and undesired EM coupling effects. Normally a compromise between size and performance is chosen [2], [3].
Figure 2: Basic structure of a MSA; where $W$ and $L$ are the patch width and length respectively, $h$ is the substrate thickness, $\varepsilon_r$ is the substrate dielectric constant and $W_0$ is the width of the microstrip line feeding [1]-[7].

2.1.2 Methods of analysis of MSAs

Due to the great advantages and applications of MSA, several methods of analysis have been developed to explain their operation [1]-[7]. In a broad sense, the methods of analysis for MSA can be divided into two main groups: methods based on magnetic current distribution and methods based on electric current distribution. The first group usually includes an analytical approach, while the second is more oriented to numerical methods [1], [3], [6], [7].

Among all the methods based on magnetic current distribution, the most popular are the transmission line (TL) model, the cavity model and the multiport network model. These methods are relatively simple and give good physical insight; but they are not very accurate. The most popular techniques based on electric current distribution are the method of moments (MoM), the finite-element method and the finite-difference time domain method. These methods have are more complex and require the use of numerical tools [1], [3], [6], [7].

Two of the mentioned methods are of special interest for this project: the TL model and the MoM. The TL model has a very simple approach and gives a good physical insight. The TL model will be used to perform analytical designs [1], [3], [6], [7], [13]. On the other hand, the MoM, based on the resolution of the integral forms of Maxwell’s equations, is a very accurate and versatile technique. The MoM is used by the 3D EM planar simulator Momentum; consequently, it will provide the results of the simulations [25], [26].

2.1.3 TL model of MSAs

As was said in the previous section, the TL model is used to provide simple design criteria in this project; consequently, a description of its principles has to be presented. The TL model is
The simplest analytical technique to describe MSAs. The TL model represents each radiating slot in a rectangular microstrip patch as two equivalent parallel admittances, with conductance $G$ and susceptance $B$, separated by a line of characteristic admittance $Y_0$. Figure 3 shows the TL model equivalent circuit representation [1], [3], [6], [27], [28]. In Figure 3 the radiating slots are identified as 1 and 2. Each radiating edge has an admittance given by equation (1), where uniform and infinitely wide slots are considered. The corresponding expressions for the conductance and susceptance are given by equations (2) and (3) [1], [3], [6], [28].

\[
Y_1 = G_1 + jB_1
\]  
\[ \text{(1)} \]

\[
G_1 = \frac{W}{120\lambda_0} \left[ 1 - \frac{1}{24} (k_0 h)^2 \right], \quad \frac{h}{\lambda_0} < \frac{1}{10} 
\]  
\[ \text{(2)} \]

\[
B_1 = \frac{W}{120\lambda_0} \left[ 1 - 0.636 \ln(k_0 h) \right], \quad \frac{h}{\lambda_0} < \frac{1}{10} 
\]  
\[ \text{(3)} \]

Where $W$ is the patch width, $\lambda_0$ is the free space wavelength, $k_0 = 2\pi/\lambda_0$ and $h$ is the substrate thickness. Equations (1), (2) and (3) are the same for both radiating slots; given that they have the same attributes.

Figure 3: (a) MSA side view including fringing fields. (b) Equivalent circuit for TL model. Each radiating slot is represented by a parallel conductance $G$ and susceptance $B$ [1], [3], [6], [27], [28].

The characteristic admittance of the patch can be expressed as equation (4), when constant fields are assumed along the direction parallel to the radiating slots [1], [3], [6], [28].
\[ Y_0 = \frac{c}{\varepsilon_r} \frac{W \sqrt{\varepsilon_r}}{h} \] (4)

Where \( c \) is the speed of light in free space and \( \varepsilon_r \) is the dielectric constant of the substrate. The importance of the model in Figure 3 is that it can provide means to find the characteristic impedance, input impedance and patch characteristics of a MSA as is explained in the next sections [1], [3], [6], [28].

2.1.4 Rectangular MSA design based on TL model

The microstrip patch dimensions are not infinitely wide as assumed by equations (1) to (4). As a result, some additional considerations have to be taken. The finite dimensions of the microstrip patch produce fringing fields from its edges to the substrate and ground plane, as can be seen in Figure 4. Fringing fields are governed by the patch dimensions and the dielectric substrate attributes [1], [3], [6], [28]. Fringing fields are not just confined into the substrate, but are also spread into the air; as a result, the dielectric constant is reduced. In addition, fringing fields produce an apparent increase of the microstrip patch dimensions. The effects of fringing fields can be described by first defining the effective dielectric constant of the substrate. For a simple analysis, equation (5) gives a good approximation for the effective dielectric constant due to fringing effects [1], [3], [6].

\[ \varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + 12 \frac{h}{W} \right]^{-\frac{1}{2}} \] (5)

**Figure 4:** Field distribution microstrip antenna operating in the TM\(_{10}\) mode [1], [3], [6], [28]

For an antenna operating in the fundamental TM\(_{10}\) mode, the patch will present constant fields along its length and varying fields along its width, such as is shown in Figure 4. Due to fringing fields the patch will look electrically larger. The length extension \( \Delta L \) of the patch can be easily predicted by the formula given in equation (6). The effective length of the patch can be defined as in equation (7), taking into account both radiating slots [1], [3], [6], [7].
\[ \Delta L = \frac{h}{\sqrt{\varepsilon_{ef}}} \quad (6) \]

\[ L_{ef} = L + 2\Delta L \quad (7) \]

The microstrip patch resonant frequency depends directly on its dimensions and the dielectric constant of the substrate. Therefore, the fringing effects produce an effective resonant frequency as well. Equation (8) shows the effective resonant frequency \( f_{re} \) produced by fringing fields \([1], [3], [6], [7]\).

\[ f_{re} = \frac{c}{2L_{ef} \sqrt{\varepsilon_{ef}}} \quad (8) \]

Equation (9) offers an expression to find \( W \), for a practical good radiator \([1], [3], [6], [7] \).

\[ W = \frac{c}{2f_r} \sqrt{\frac{2}{\varepsilon_r + 1}} \quad (9) \]

Where \( f_r \) is the resonant frequency. Equations (5) to (9) represent a useful set of equations that has been extensively used in antenna design. Equations (5) to (9) can provide a good predictions; however, they are not completely accurate \([1], [3], [6], [7] \). This project pretends to use these equations to develop analytical designs and compare results with Momentum simulations.

### 2.1.5 Input impedance and feeding network position

The patch length in resonance is equal to \( \lambda/2 \); however, due to fringing fields the physical separation between slots is slightly smaller. Considering length reduction and using admittance transformation concepts, it is possible to find the admittance of slot 2 at resonance, given by equation (10) \([1], [3], [6], [7] \).

\[ \tilde{Y}_2 = \tilde{G}_2 + j\tilde{B}_2 = G_1 - jB_1 \quad (10) \]

Consequently the total input admittance at resonance considering slot 1 and slot 2 is given by equation (11). The total input impedance of the microstrip patch is real at resonance and corresponds to the reciprocal of the input admittance, as shown in equation (12) \([1], [3], [6], [7] \).

\[ Y_{in} = G_1 + jB_1 + \tilde{G}_2 + j\tilde{B}_2 = 2G_1 \quad (11) \]

\[ Z_{in} = R_{in} = \frac{1}{2G_1} \quad (12) \]
The input impedance given by (12) is referred to the edge of the microstrip patch; but if a feeding network is placed in an inset position it can change the input impedance. If a coaxial probe feeding is considered and placed in an inset position $y_0$, such as in Figure 5, the input impedance at resonance can be approximated by equation (13) [1], [3], [6], [7].

$$R_{in}(y = y_0) = R_{in} \sin^2 \left( \frac{n \pi}{L} y_0 \right)$$

Equation (13) can be used to find a position where the feeding network could provide input impedance matching, without the need of a matching network [1], [3], [6], [7]. Consequently, equation (13) is an important design expression for analytical designs.

![Coaxial probe feed at position $y_0$](image)

**Figure 5**: Coaxial probe feed at position $y_0$ [1], [3], [6], [7].

### 2.1.6 Coplanar waveguide (CPW) theory and design

Coaxial and microstrip-line are the most employed feeding networks in MSAs, due to their simple analysis and development; however, they have some important disadvantages. In the case of coaxial lines, there are size constrains for antennas operating in the millimetre wave bands. Similarly, microstrip lines exhibit disadvantages like characteristic impedance dependant on the substrate thickness. In addition, a microstrip line has the ground plane located in the opposite side of the substrate, creating difficulties for shunt connections and integration into MMICs [6], [7], [29]-[32].

Due to all the drawbacks of coaxial probes and microstrip lines, alternative structures were developed. One of the most used is the coplanar waveguide (CPW). The CPW consists of a centre conducting strip placed in between of two ground electrodes, above a dielectric substrate, such as Figure 6 illustrates [6], [29], [31], [33], [34], [35]. The CPW presents several advantages in comparison to coaxial and microstrip feeds. First of all, a CPW has the conducting and ground elements in the same plane; leading to ease of series and parallel connections in MICs. Also, the characteristic impedance of a CPW does not show a strong dependence with the
substrate thickness. Finally, CPWs have shown to be compatible with MMIC technology [6], [7], [29]-[32].

Figure 6: CPW generic structure, where $a$ is distance from the middle point to the edge of the conducting strip and $b$ is distance from the middle point of the conducting strip to the edge of the ground electrode [6], [29], [31], [33], [34], [35].

The characteristic impedance of a CPW can be found by using conformal mapping techniques. The characteristic impedance of a CPW with finite substrate thickness and finite ground planes is given by equation (14). An effective dielectric constant $\varepsilon_e$, given by equation (15), needs to be considered [6], [29], [31], [33], [34], [35].

$$Z_{0cp} = \frac{30\pi}{\sqrt{\varepsilon_e}} \frac{K'(k)}{K(k)}$$  \hspace{1cm} (14)

$$\varepsilon_e = 1 + \frac{\varepsilon_r - 1}{2} \frac{K'(k) K(k_1)}{K(k) K'(k_1)}$$  \hspace{1cm} (15)

Where $Z_{0cp}$ is the characteristic impedance of the line, $k$ and $k_1$ are parameters related to the CPW dimensions $a, b$ as shown in equations (16) and (17), and the ratio $K(k)/K'(k)$ represent elliptic functions described by equations (18) and (19) [6], [29], [31], [33], [34], [35].

$$k = \frac{a}{b} \sqrt{\frac{1 - b^2/c^2}{1 - a^2/c^2}}$$  \hspace{1cm} (16)

$$k_1 = \frac{\sinh(\pi a/2h)}{\sinh(\pi b/2h)} \sqrt{\frac{1 - \sinh^2(\pi b/2h)/\sinh^2(\pi c/2h)}{1 - \sinh^2(\pi a/2h)/\sinh^2(\pi c/2h)}}$$  \hspace{1cm} (17)

$$\frac{K(k)}{K'(k)} = \frac{\pi}{\ln[2(1+\sqrt{k^2})/(1-\sqrt{k^2})]} \text{ for } 0 \leq k \leq 0.707$$  \hspace{1cm} (18)
\[
\frac{K(k)}{K'(k)} = \frac{\ln\left[\frac{2(1+\sqrt{k})}{(1-\sqrt{k})}\right]}{\pi} \quad \text{for } 0.707 \leq k \leq 1
\] (19)

Equations (14) to (19) are the set of equations used in this work to design the CPW feeding network [6], [29], [31], [33], [34], [35].

2.1.7 Multilayer GaAs MMIC technology

The technology of MMICs based on GaAs substrates has attracted the attention of researchers and industry. The reason is that multilayer GaAs MMICs present several advantages over other conventional MIC technologies such as: carrier mobilities six times faster than silicon (Si), low production cost, small size, high stability and good broadband performance. These advantages become more interesting for systems working at frequencies higher than 20GHz, due to the inherent small size of MMICs and the substantial reduction on line loss when frequency increases. When operation is near the millimetre wave range, MMICs have shown considerably better performance than other MICs [9], [15], [36]-[39].

The advantages of GaAs MMICs combined with their good performance in high frequency operation, are the reasons to use this technology in millimetre wave antenna development. The difference between MMICs and other MICs technologies resides in the use multilayer structures instead of conventional planar configurations. MMIC technology is able to allocate circuit components and blocks in different layers, thus reducing device size and manufacture costs [9], [15], [36]-[39]. These are the reasons to design antennas based in GaAs MMICs in this project.

A very illustrative example concerning GaAs technology is shown in Figure 7, which depicts an antenna explored in the works of Somarisi et al [13], [14] and Sánchez-Hernández et al [9]. This example is especially interesting for this project since it combines GaAs MMICs with CPW feeding. As can be seen in Figure 7, the feeding network and two patch radiators are located in different layers. These kind of multilayer MMIC structures have the potential of reducing considerably size of antennas. It has been shown that MMICs can be the basis to achieve the integration of entire transceivers in a single chip [9], [15].
2.1.8 Multilayer effective dielectric constant

When multilayer structures are considered, the effective dielectric constant of a microstrip patch antenna cannot be described by equation (5) any longer. The additional layers modify the effective length due to fringing fields and the resonant frequency. Figure 8 shows a microstrip patch embedded in a three dielectric layer structure, presented in the works of Zhong et al [40] and Garg et al [6].

The effective dielectric constant for the structure in Figure 8 can be found using conformal transformations and can be easily extended to more layers. Equation (20) shows the expression for the quasistatic effective dielectric constant for the configuration of Figure 8 [6], [40].

\[
\varepsilon_{eff} = \varepsilon_{r1}\varepsilon_{r2}\frac{(q_1 + q_2)^2}{\varepsilon_{r1}q_2 + \varepsilon_{r2}q_1} + \varepsilon_{r3}\frac{(q_1 + q_2)^2}{\varepsilon_{r1}(1 - q_1 - q_2 - q_3) + q_3}
\]  

(20)

Where \(q_1, q_2, q_3\) are factors related to the conformal mapping procedure given by equations (21) to (23) [6], [40].
\[ q_1 = \frac{h_1}{2h_{12}} \left( 1 + \frac{\pi}{4} - \frac{h_{12}}{W_e} \ln \left[ \frac{2W_e}{h_1} \sin \left( \frac{\pi h_1}{2h_{12}} \right) + \cos \left( \frac{\pi h_1}{2h_{12}} \right) \right] \right) \] (21)

\[ q_2 = 1 - q_1 - \frac{h_{12}}{W_e} \ln \left( \frac{\pi W_e}{h_{12}^2} - 1 \right) \] (22)

\[ q_3 = 1 - q_1 - q_2 = \frac{h_{12} - v_e}{W_e} \ln \left[ \frac{2W_e}{2h_{13} - h_{12} + v_e} \cos \left( \frac{\pi v_e}{2h_{12}} \right) + \sin \left( \frac{\pi v_e}{2h_{12}} \right) \right] \] (23)

Here, \( W_e \) is the effective patch width given in equation (24) and the factor \( v_e \) is defined in equation (25) [6], [40].

\[ W_e = W + \frac{2h_{12}}{\pi} \ln \left[ 17.08 \left( \frac{W}{2h_{12}} + 0.92 \right) \right] \] (24)

\[ v_e = \frac{2h_{12}}{\pi} \tan^{-1} \left[ \frac{2\pi}{\pi W_e - 4h_{12}} (h_{13} - h_{12}) \right] \] (25)

The set of equations (20) to (25) can be used to find good analytical approximation for the effective dielectric constant of multilayer structures [6], [40]. As a consequence, equation (20) is going to be used instead of equation (5) through this project [6], [40], [41].

### 2.1.9 Bandwidth definition

The bandwidth (BW) of a MSA is usually defined in terms of the input Voltage Standing Wave Ratio (VSWR). BW is commonly described as the frequency range in which the input VSWR is less than a specific value, which is usually taken as 2. This BW is customarily expressed as a fraction of the resonant frequency, called fractional BW. The definition VSWR is given by equation (26) and the expression of fractional BW is given by equation (27) [3]-[7], [16].

\[ VSWR = \frac{1 + |\Gamma_{in}|}{1 - |\Gamma_{in}|} \] (26)

\[ BW(\%) = \frac{\Delta f}{f_0} \times 100\% \] (27)

Where \( \Gamma_{in} \) is the input reflection coefficient or input return loss of the antenna, \( f_0 \) is the antenna resonant frequency and \( \Delta f \) is the frequency range where VSWR is less than 2 [3]-[7], [16]. \( \Gamma_{in} \) is
a measure of the reflected power at the feed point of the antenna. It is defined in terms of the input impedance of the antenna $Z_{in}$ and the characteristic impedance of the feeding network $Z_0$, as expressed in equation (28). In terms of S-parameter definitions $\Gamma_{in}$ is represented by the $S_{11}$ parameter [3]-[7], [16], [42].

$$\Gamma_{in} = \frac{Z_{in} - Z_0}{Z_{in} + Z_0}$$  \hspace{1cm} (28)

BW can also be defined from the radiation characteristics of the antenna [3]-[7], [16], [42]. Nevertheless, this project is only concerned with VSWR and fractional bandwidths.

### 2.1.10 Broadband and multi-frequency antennas

As was mentioned before, MSAs have a great number of advantages compared to other conventional microwave antennas; however, they are not perfect and suffer from some limitations. The most important shortcoming is their inherent narrow BW, typically in the range of 1% to 5%. As a consequence, BW enhancing has been one of the most explored topics in MSA research [1]-[7], [16]. Several techniques have been proposed to increase the BW of MSAs. Some of the most successful are: substrate modification, use of impedance matching networks, multilayer structures, patch shape modifications and use of multiple planar resonators [5]-[7], [16]

All these techniques have been applied to MSAs and in some cases have shown outstanding results, achieving fractional BWs as high as 70%. It is important to mention that all these techniques can be modified and extended to the development of multi frequency antennas, instead of just incrementing the BW [5]-[7], [16]. One of the objectives of this work is to design an antenna that would provide dual frequency operation in the millimetre wave range. As a consequence, one of these BW enhancing techniques is going to be explored: the use of planar multiresonators

### 2.1.11 Multiresonator structures for dual frequency operation

Some modern systems operate in two frequencies that are far apart from each other. A device providing this operation is referred as dual frequency antenna (DFA). Several applications require DFAs, such as wireless local area networks (WLAN), satellite links, mobile communications and radar systems. A single antenna operating in two different frequencies is a very attractive solution, since it can avoid the use of multiple devices; reducing systems size and cost [5]-[12]. It convenient to mention that there is a difference between the terms dual band and dual frequency antennas. A dual band antenna supposes the presence of two close resonant
frequencies within a determined BW. On the contrary, a dual frequency antenna implies operation in two far apart frequencies [5]-[12].

As was said before, DFAs can be designed by using BW enhancing techniques. This work is particularly focused in exploring the planar multiresonator technique that uses the principle EM parasitic coupling. An additional resonant frequency can be produced, without the need of an extra feeding network, when a parasitic patch is coupled to a fed patch. If both resonant frequencies are close to each other, the system can lead to broad BW. On the other hand, if the two resonant frequencies are far apart from each other, dual-frequency operation in achieved [5]-[7], [16].

Figure 9 shows an example of a fed patch with one parasitically coupled patch, to illustrate the mechanism of multiresonator structures. In Figure 9, the fed patch produces the resonant frequency $f_1$, while the parasitic patch produces $f_2$. The operation of this kind of structure depends on several parameters such as: gap distance between patches, location of parasitic elements along radiating or non-radiating slots and patch dimensions [5]-[7], [16]. Figure 10 shows two examples of planar multiresonator configurations developed in past works. These configurations provide good performances for dual band operation, but at a very high cost: increasing device size. Device size is one of the most (if not the most) important parameters in modern communication systems design. This is the main motivation to explore an alternative configuration proposed in the works of Aanandan et al [17]-[19].

**Figure 9**: (a) Rectangular fed microstrip patch with one patch parasitically coupled patch to the radiating edge. (b) Dual frequency response produced by the fed patch ($f_1$) and the parasitically coupled patch ($f_2$) [5]-[7], [16]
Aanandan et al proposed a structure based in dividing a main patch into a multiresonator configuration, rather than adding extra parasitic patches. Figure 11 shows this structure, where narrow patches are located next to a central fed patch, along the non-radiating edges. All the resonators have equal length but different widths. Since resonant frequency is a function of patch width, the structure achieves multiple resonances, which in turn increases the BW. This antenna provided a BW of nearly 10 times the BW of a single patch with the same overall area. In addition the size of the resonators is compact; as a result, the size of the entire structure is compact as well [5], [7], [16]-[19].

This work pretends to explore the characteristics of the antenna in Figure 11 to develop a DFA, instead of a broadband antenna. The multiresonator antenna, proposed by Aanandan et al [17]-[19] shows compact characteristics; as a consequence it is an excellent candidate for millimetre wave systems. Furthermore, this particular structure has not been reported as a DFA and design procedures have not been proposed either.
2.2 Literature Review of GaAs MMIC antennas and dual frequency antennas (DFAs)

This section is focused in providing a review of important past works and publications, related to GaAs MMIC antennas with CPW feeding and DFAs based in planar multiresonator configurations.

2.2.1 GaAs MMIC antennas with CPW feeding

There are very interesting examples of antennas developed in the GaAs MMIC technology with CPW feeding, since this combination supposes great advantages for antenna performance. Furthermore, there are some works that already reported designs of multi frequency antennas using GaAs MMIC technology with CPW feeding; although, using different techniques in comparison to the multiresonator structure proposed in this project. The most relevant publications in this context are mentioned below.

The work of Sánchez-Hernández et al [9] presents the design and construction of antennas in GaAs MMIC technology, working around 35GHz. The publication presents two main types of antennas: a stacked patch antenna and a spur-line antenna. Both are developed to work as dual band antennas. In the stacked patch antenna a multilayer structure, such as the one presented in Figure 7, is developed to provide dual band operation. The lower patch is fed by a CPW, while an upper patch is parasitically coupled. The result is a successful dual band operation based in the principle of EM coupling. On the other hand the spur-line antenna uses an efficient notch filter to provide dual band operation. The paper of Sánchez-Hernández et al [9] also explores the use of CPW and is shown that CPW can provide good results for millimetre wave antennas. Consequently, the publication by Sánchez-Hernández et al [9], represents a very important reference for design and simulation purposes.

A publication following the same approach is reported in the work of Somarisi et al [13]. This publication explores the stacked patch antenna, also presented in [9], but developing a simulation based in the Finite-Difference Time-Domain (FD-TD) method. This publication reports the use of the Transmission Line (TL) model to provide design insight for the antenna. This paper does not present much detail about analytical design or antenna performance.

Another interesting work concerning MMICs and CPW can be found in the publication of Vo et al [30]. In this paper several CPW structures are designed and manufactured in multilayer GaAs MMIC technology. Vo et al [30] show that it is possible to manipulate a CPW in such way that
specific impedance and return loss can be obtained. This paper points out the great potential and possibilities offered by CPWs in multilayer GaAs MMIC devices.

There are plenty of works reporting the combination of MMIC technology with CPW feeding networks. However, the publications mentioned in this section represent very important examples for the purposes of this project. They reported good results and obtained devices with suitable performance. The dual band antennas explored by [9] and [13] are somehow the models followed to develop a dual frequency antenna in this project.

2.2.2 DFAs based on planar multiresonator structures

Planar multiresonator structures are among the most popular techniques to produce dual frequency operation; consequently, there are plenty of publications in this matter. One of the most complete reports about dual frequency antennas is given in Kumar and Ray [7]. This book is mostly concerned about broad-band antennas, but there are complete chapters devoted to dual frequency antennas and multiresonator structures. This book contains a very detailed survey of the most popular techniques for broad-band and multi-frequency antenna development. Chapter 3 of the book of Kumar and Ray [7] offers a design guidelines for planar multiresonator antennas. The procedure explained is based in semi-empirical methods and shows a parametric study.

Another interesting report that presents a survey in bandwidth extension techniques is offered by Gupta [16]. This report exhibits the most popular techniques to develop broad-band antennas. The techniques presented are substrate modification, impedance matching, multilayer and multiresonator structures. A special emphasis is devoted to explain the advantages and disadvantages of each one technique.

The reports offered by [7] and [16] represent a very complete source of information for the study of dual frequency antennas. These works present a summary and a review of wide range of papers dedicated to broadband and multi band techniques development [7], [16]. This is the reason to use them as the main guidelines to develop the multiresonator antenna in this project. It is very important to mention that both reports make a quick treatment of the multiresonator structure reported in the works of Aanandan et al [17]-[19]. The advantages of the antenna in Figure 11 are well commented, but a details regarding design are not presented. Both [7] and [16] mention that complete analysis or design procedures for this type of antenna have not been reported and recommend further investigations.
CHAPTER 3: METHODOLOGY AND SIMULATION PROCEDURES

As was mentioned in the objectives of this project, it is desired to design and simulate two types of antennas: a single patch antenna and a dual frequency antenna (DFA). Both antennas will be designed in the multilayer GaAs MMIC technology using coplanar waveguide (CPW) feeding. Operation will be considered around 35-50GHz. This chapter presents the analytical designs and simulation procedures of both antennas. In addition, a description of the software employed is offered. The chapter will be divided in three main parts: description of software platforms, methodology for single patch antenna and methodology for dual frequency antenna.

3.1 Software Platforms Characteristics

The antennas in this project are developed following two stages, analytical design and simulations. MATLAB is the software used to handle the analytical process. The transmission line (TL) model equations, introduced in Section 2.1, are implemented in MATLAB. On the other hand, the 3D planar electromagnetic (EM) simulator Momentum is used to perform simulations based on the Method of Moments (MoM). Software generalities and their specific applications in this project are explained below.

3.1.1 MATLAB

MATLAB is one of the most employed software in engineering and science. MATLAB combines a data analysis environment and a high level programing language. MATLAB have been applied to the development of products and systems in many fields such as: mobile communications, aircraft design, signal processing, control systems and even robotics. MATLAB features a matrix-based language, which can be used to perform advance mathematical computations and implement algorithms [43].

In this project MATLAB is used to implement the TL model equations for microstrip antennas (MSAs). By writing MATLAB programs, it will be possible to perform fast and reliable analytical designs. Since TL model equations are not mathematically complex, designs will not incur in computer overhead. It is desired to implement the TL model equations to find microstrip patch dimensions, antenna input impedance and feeding network characteristics. As mentioned in Chapter 2, the TL model cannot describe accurately MSAs operation; consequently, the
equations implemented in MATLAB are used to provide design insight for the subsequent simulations in Momentum.

### 3.1.2 Keysight Advance Design System (ADS) Momentum

Momentum is a 3D planar EM simulator integrated into Keysight Advance Design System (ADS). Momentum is based in the MoM, which uses surface currents to model a microstrip patch and volumetric polarization currents to model fields in the dielectric material. Integral equations are used to find unknown currents and later are translated into algebraic formulas that can be solved by computational means. It is worth to mention that MoM considers the influence of fringing fields, thus producing very accurate descriptions of MSAs [3], [7], [25], [26], [44].

Momentum performs calculations based in the MoM to find S, Y and Z-parameters of planar circuits. Momentum is capable to analyse arbitrary shapes and can provide accurate results for MSAs and CPWs. Momentum overcomes limitations of other simulators, since it considers parasitic EM coupling and can perform accurate simulations even in conditions where circuit models are physically far apart [25], [26], [44]. In this project Momentum is employed to perform EM simulations of the single patch antenna and the dual frequency antenna, to obtain results based in the MoM.

### 3.1.3 Momentum simulation procedures for MSAs

The simulation of an antenna in Momentum can be performed following three steps: creation of Layout, definition of Substrate and simulation setup. Momentum is used to simulate MSAs in this project and all the given descriptions are exclusively concerned with them. Momentum features for other devices are not commented.

In first place, a planar model of the antenna has to be created in a Layout. A Layout is an environment in which any planar geometry can be generated. A Layout has a modelling scheme based in dividing a model in separate layers. Although a Layout is just a 2D environment, it is possible to construct multilayer structures [25], [26], [44]. Figure 12 shows an example of a Momentum Layout, where a model of a rectangular patch antenna, with microstrip feeding, is depicted.

The second step to antenna simulations consists in determining layers characteristics in a separate capability: the Substrate Editor. The Substrate Editor provides means for defining layer materials and thicknesses. Furthermore, the Substrate Editor can specify the existence of connections between layers. Figure 13 shows an example of a model created with Substrate Editor. From now on, the models of the Substrate Editor will be just called Substrate. Figure 13 is the Substrate created to define layer materials and thicknesses for the Layout of Figure 12.
Figure 12: *Layout* of a rectangular patch MSA, with microstrip line feeding.

Figure 13: *Substrate* example of a rectangular patch antenna. (i) Ground plane. (ii) GaAs substrate of 100μm thickness. (iii) Conductor layer corresponding to microstrip patch. (iv) Air.

The setup of EM simulations is the last step for antenna analysis in Momentum. There are two types of EM simulations: RF and Microwave. RF simulations perform quasi-static studies and are mostly used for non-radiating devices, as they do not provide information about radiation patterns. On the other hand, Microwave simulations perform full-wave analysis and are conceived for radiating elements. In this project Microwave simulations are exclusively used. There are other simulation setups, like port definitions and meshing configuration, which are explained in more detail in Chapter 4.

The antennas simulated in this project, will follow the three step procedure described in this section: *Layout* creation, *Substrate* definition and simulation setup. Results obtained in Momentum will be compared with analytical designs in order to observe differences between both. The next sections address the methodology used to develop the single patch and the dual frequency antennas.

### 3.2 Single patch antenna design

The main aim of this project is to design and simulate an antenna to provide dual frequency operation around 35-50 GHz. To accomplish this goal the first step consists in developing a
single patch antenna, which will provide general design guidelines. This means that both the single patch and the dual frequency antenna will share some common procedures. Procedures concerning the single patch antenna design are explained in the following sections.

### 3.2.1 Variables considered for performance analysis

This work is focused in analysing return loss, resonant frequency, input impedance and bandwidth of the designed antennas. The objective of this project is to generate dual frequency operation and the variables mentioned provide the means to correctly examine results in this context. This project would not study radiation parameters of antennas; which is a topic suggested for future works.

### 3.2.2 Single patch antenna structure

To begin with the single patch antenna design it is necessary to define its structure. It is desired to design this antenna based in two premises: the use of the multilayer GaAs MMIC technology and the use of CPW feeding. The single patch antenna is designed to work around 35 GHz, corresponding to millimetre wavelengths; consequently, its dimensions will be close to a few millimetres. The structure proposed for the single patch antenna is shown in Figure 14. In this structure two metallic layers and a dielectric layer are placed above a semi-insulating GaAs substrate. The metallic layers will be referred as Metal 1 and Metal 2.

The thickness of each layer is identified in Figure 14, where the GaAs substrate ($\varepsilon_r=12.85$) is has a thickness of 400 μm. Metal 1 is placed above the GaAs substrate, to accommodate the CPW and has a thickness of 1 μm. A dielectric layer, made of Poyimide ($\varepsilon_r=12.85$), is placed over Metal 1 with a thickness of 2 μm. Finally, Metal 2 is located on top of the whole structure with 1 μm thickness to accommodate the radiating patch. Metal 1 and Metal 2 layers are connected via a metallic shorting pin that goes through the Polyimide layer. This shorting pin feeds the microstrip patch.

This multilayer structure presents the great advantage of reducing planar dimensions, given that feeding network and the microstrip patch are located in different layers. This structure has the potential of reducing manufacturing costs and showed compatibility with GaAs MMICs. In addition the feeding technique is based in a shorting pin, which can be explained by means of coaxial probe approximations [1]-[7]. This structure was already proposed in the works of Sánchez-Hernández et al [9] and Somarisi et al [13]. The main reason to use it in this project are successful simulation and practical results for operation around 35GHz [9], [13], [14]. However, it is very important to mention that the structure in Figure 14 has not been used to develop a dual frequency antenna based in multiresonators before.


**Figure 14:** Single patch antenna structure. Layers are: (i) GaAs substrate: 400 μm. (ii) Metal 1: 1 μm (iii) Polyimide: 2 μm. (iv) Metal 2: 1 μm.

### 3.2.3 Microstrip patch analytical design

TL model equations are used to design the microstrip patch for the antenna in Figure 14. Since it is a multilayer structure the principles presented in Section 2.1.8, with respect to the effective dielectric constant, have to be considered. TL analytical design is used to provide approximate dimensions and characteristics to develop good simulations in Momentum. The results provided by the analytical analysis are going to be used to create the Momentum Layouts.

Transmission line model equations were introduced in Chapter 2, but they are replicated in this section for clarity purposes. The first step to develop patch design is to determine resonant frequency. In this case it is desired to design a patch to operate at 35GHz. Using this resonant frequency it is possible to find the patch width by equation (29) [1] [3] [6] [7].

\[ W = \frac{c}{2f_r \sqrt{\epsilon_r + 1}} \]  

(29)

Where \( f_r = 35\text{GHz} \) is the resonant frequency, \( c \) is the speed of length in vacuum, and \( \epsilon_r \) is the dielectric constant. For the sake of simplicity \( \epsilon_r \) is assumed as the GaAs dielectric constant. However, for the subsequent calculations the multilayer effective dielectric constant is considered. The effective dielectric constant due to fringing effects can be found using equation (30) [6], [40].

\[ \epsilon_{eff} = \epsilon_{r1} \epsilon_{r2} \frac{(q_1 + q_2)^2}{\epsilon_{r1} q_2 + \epsilon_{r2} q_1} + \epsilon_{r3} \frac{(q_1 + q_2)^2}{\epsilon_{r1} (1 - q_1 - q_2 - q_3) + q_3} \]  

(30)

Where \( \epsilon_{r1} = 12.85 \) is the GaAs dielectric constant, \( \epsilon_{r2} = 3.5 \) is the Polyimide dielectric constant and \( \epsilon_{r3} = 1 \) is the air dielectric constant. The terms \( q1, q2, q3 \) can be found by the equations described.
in Section 2.1.8. Then, it is necessary to define the patch length. This can be accomplished by finding the length extension due to fringing fields using equation (31) and then using equation (32).

\[ \Delta L = \frac{h_{12}}{\sqrt{\varepsilon_{\text{eff}}}} \]  

(31)

\[ L = \frac{c}{2f_{r}\sqrt{\varepsilon_{\text{eff}}}} - 2\Delta L \]  

(32)

Where \( h_{12} \) is the combined thickness of GaAs and Polyimide layers. Equations (29) to (32) are the basis of the analytical design of the microstrip patch. As was explained before, these equations are going to be implemented in MATLAB to produce a fast and reliable analysis.

### 3.2.4 Coplanar Waveguide characteristics for single patch antenna

A CPW is used to feed the microstrip patch, using a shorting pin. It is necessary to determine CPW dimensions, in order to obtain characteristic impedance. Also, it is required to find the shorting pin position that will provide impedance matching. The equations describing CPW design were defined in Section 2.1.6 and are reproduced here for clarity purposes.

It is desired to design a 50 \( \Omega \) CPW, since it is a standard in microwave circuits and antenna design [1]-[7], [42]. The CPW dimensions to obtain 50 \( \Omega \) characteristic impedance can be found by equations (33) and (34).

\[ Z_{\text{0cp}} = \frac{30\pi}{\sqrt{\varepsilon_e}} \frac{K'(k)}{K(k)} \]  

(33)

\[ \varepsilon_e = 1 + \varepsilon_r - \frac{1}{2} \frac{K'(k) \ K(k_1)}{K(k) \ K'(k_1)} \]  

(34)

Once the dimensions and characteristic impedance of the CPW are established, it is possible to find the specific feeding location that will provide impedance matching. The CPW is connected to the patch by a shorting pin, which resembles a coaxial probe. It has been shown that good approximations are obtained using coaxial probe equations for shorting pin designs [45], [46]. The shorting pin position for impedance matching can be found using equation (35).

\[ R_{\text{in}}(y = y_0) = R_{\text{in}}\sin^2 \left( \frac{\pi}{L} y_0 \right) \]  

(35)

Where \( R_{\text{in}}(y = y_0) \) is the input resistance of the microstrip patch at a position \( y_0 \), \( R_{\text{in}} \) is the input resistance of the microstrip patch at resonance and \( L \) is the patch length. Equation (35) is
manipulated to find a position $y_0$ where the input impedance would be equal to 50 $\Omega$. In summary, equations (34) to (35) provide a procedure to find CPW dimensions and position to achieve matching.

### 3.2.5 Momentum simulation for single patch antenna

The final step in the single patch antenna design involves Momentum simulations. As was stated in Section 3.1.3, the antenna simulation follows three steps: creation of Layout, Substrate definition and EM simulation configuration. In first place, a Layout containing a rectangular microstrip patch and a CPW will be created. The Layout models will be created following the results from analytical designs. Later, Substrate will be defined using layer thickness and materials specified in Figure 14. The material used for the metallic layers will be gold, since it is a widely used material in microwave circuits and antenna development [4], [5], [6]. Finally the EM simulations will be configured as: Microwave analysis. Analytical predictions will be compared with simulation results and will be used as a reference to design the dual frequency antenna.

### 3.3 Dual frequency antenna (DFA) design

The aim of this project is to design and simulate a DFA, based in the principle of dividing a single patch into smaller resonators. Descriptions of this kind of antenna were introduced in Section 2.1.11. A DFA designed with a multiresonator structure, in GaAs MMICs with CPW feeding has not been reported yet; consequently, developing such device represents a novel study. This section offers a detailed explanation of the antenna structure. In addition, the methodology followed to design the antenna is presented.

#### 3.3.1 Multiresonator DFA antenna structure

The antenna in Figure 11 has proven to offer a BW around 10 times the BW of a single patch antenna with the same overall area. In the works of Aanandan et al [17]-[19], this antenna was developed dividing a microstrip patch into 5 to 7 narrow resonators. In this work, this antenna will be used to develop a DFA and will use three resonators: a central fed patch and two parasitically coupled strips. Figure 15 shows the proposed structure, where the three patches have the same length and both parasitic patches have equal width.

The main motivation to propose the structure in Figure 15 is the possibility to obtain an antenna with similar operation than a single patch antenna; but providing an extra resonant frequency without size increment. In other words, the structure in Figure 15 will be designed in such way that could provide one resonant frequency similar to the single patch antenna of Section 3.2 and
an extra resonant frequency inside 35-50GHz. The interesting part of this design is that planar area enlargement is not necessary.

The theoretical principle that describes this antenna is extra resonant frequencies produced by parasitic patches [5]-[7]. For example, in the antenna if Figure 15 the central patch will produce a resonant frequency, while the two parasitic patches will produce an additional operation frequency. Although there are two parasitic patches, just one additional resonant frequency is produced because both parasitic patches have equal dimensions. This particular structure has the advantage of symmetry, since both gaps between main patch and parasitic elements have equal size.

The design procedure for this antenna will follow the same principles defined for the single patch antenna. The antenna structure is the same as Figure 14, but with the patch divided in three resonators. Figure 16 shows a scheme of the proposed DFA. The only significant difference between the single patch antenna and the DFA is the division of the main patch into three resonators. The structure in Figure 16 has not been reported to design a dual frequency antenna to work around 35-50GHz; consequently, is here where the novelty of the project resides. If successful dual frequency operation can be produced, interesting new findings and conclusions can emerge.

![Diagram of a dual frequency antenna](image)

**Figure 15:** Top view of Proposed Dual frequency antenna. $L$ is the patches length, $W$ is the width of the central patch, $W_1$ is the width of the parasitic patches.
3.3.2 Multiresonator antenna analytical design

Analytical design of the multiresonator antenna will follow almost the same procedures used for the single patch antenna. Patch sizes will be determined by equations (29) to (32) and CPW characteristics by (33) to (35). However, multiresonator designs require some additional considerations. The most important is that analytical procedures for multiresonator structures are not available in the literature and methods used are mostly empirical. Consequently, an analytical design of this antenna will not provide accurate predictions and an empirical optimization in Momentum will be strictly necessary. The design of this antenna requires two steps: determinations of centre and parasitic patches dimensions and identification of gap size.

In the work of Kumar and Ray [7] there is an interesting treatment of multiresonator structures and a semi-empirical procedure is offered to design gap coupled antennas. Some of the procedures suggested in [7] are followed here. The first step in the DFA design is to find the resonant frequency and dimensions of the central patch. It is expected to produce at least one resonant frequency close to the single patch antenna operation at 35GHz.

Given that three resonators are present in the structure, the centre patch of the DFA will be designed to be less than one third of the single patch antenna area. As the resonant frequency is inversely proportional to the patch dimensions, the centre patch is expected to have a higher resonant frequency than the single patch antenna. Then, it is necessary to determine the size of the parasitic patches. Since the centre patch will provide a resonant frequency higher than the single patch antenna, it is desired to obtain a lower resonant frequency from the parasitic patches. In this way it will be possible to obtain at least one resonant frequency close to the 35GHz of the single patch antenna. As a result, the parasitic patches will be slightly wider than the centre patch.
The final step in the DFA design consists in determining the gap size between the centre and the parasitic patches. However, it is not possible to determine the size of the gaps by analytical means; because simple EM coupling equations are not available. EM coupling can only be accurately predicted by more complex methods like the MoM [1]-[7], [34], [35]. Kumar and Ray [7] suggest an empirical procedure to find the gap size. When parasitic patches are coupled along non-radiating edges, coupling is not very strong; thus, a small gap should be used. It is recommended test several gaps starting around 0.3 times the substrate thickness and perform tests until desired operation is obtained.

In summary, DFA dimensions and gap size will be found combining analytical and empirical approaches. The most important objective is to obtain dual frequency operation inside the 35-50GHz, without increasing the size compared to a single patch antenna operating around 35GHz.

3.3.3 Momentum simulation and parametric study of dual frequency antenna

Momentum will be extensively used to optimize the DFA because analytical design is not accurate. The simulations in Momentum will follow the same procedure already explained for the single patch antenna: Layout creation, Substrate definition and EM Microwave simulations. The difference between the single patch antenna and the DFA is that most of the design will be performed in Momentum, where dimensions and feeding position of the multiresonator antenna will be optimized.

In order to obtain a successful antenna optimization a careful parametric study will be conducted. By using a parametric study it will be possible to observe how specific antenna parameters affect its performance. It is desired to modify five antenna parameters to observe their effects in operation. The parameters to manipulate are: the centre patch length, the parasitic patches length, parasitic patches width, the gap size and CPW position.

In every case the parameters will be varied around the design values. Ten tests will be performed for every parameter: five tests with larger dimensions than design and five tests with smaller dimensions than design. For example if the centre patch length is found to be 1 mm, five larger dimensions and five smaller will be tested leaving all the other parameters constant. The parametric study is explained in more detail in Chapter 4.
CHAPTER 4: RESULTS AND DISCUSSION

This chapter presents all the results obtained from analytical designs and the simulations of the single patch antenna and the dual frequency antenna (DFA). Since two antennas are developed, the chapter is divided into two main sections: results concerning single patch antenna and results concerning DFA. As was stated in Chapter 3, antennas performance is evaluated in relation with: resonant frequency location, return loss, input impedance and VSWR bandwidth (BW). Therefore, all results are presented as tables and graphs involving these specific parameters.

4.1 Single patch antenna results

This section presents the results concerning the single patch antenna analytical design and Momentum simulations. Results concerning the transmission line (TL) design are presented at first. Later, Momentum Layout, Substrate and setup used for this antenna are shown. Finally results obtained in the simulations are discussed.

4.1.1 Analytical design of single patch antenna

The single patch antenna is designed using TL model equations considering a resonance frequency of 35 GHz and the structure in Figure 14. The results of applying equations (29) to (32) for the design of the microstrip patch are shown in Table 1. The results show a patch width of 1.6 mm and length of 1.2 mm for resonance at 35GHz. The patch dimensions are compact and could be perfectly integrated into modern communication equipment and an antenna with this size is perfectly applicable in satellite, radar and mobile communications [9], [13], [14]. It is worth to notice in Table 1 that fringing fields produce an effective patch length of 1.5 mm, which is 25% larger than the 1.2 mm physical length. This shows the importance of considering fringing fields, since a 25% longer length can change the resonant frequency and can be prejudicial in systems with narrow bandwidths.

Table 1: Microstrip patch characteristics for 35 GHz operation

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch Width, ( W ) [mm]</td>
<td>1.6</td>
</tr>
<tr>
<td>Patch Length, ( L ) [mm]</td>
<td>1.2</td>
</tr>
<tr>
<td>Length extension, ( \Delta L ) [mm]</td>
<td>0.142</td>
</tr>
<tr>
<td>Effective patch Length, ( \bar{L} ) [mm]</td>
<td>1.5</td>
</tr>
<tr>
<td>Effective dielectric constant, ( \varepsilon_{eff} )</td>
<td>7.996</td>
</tr>
</tbody>
</table>
Table 1 also shows the effective dielectric constant obtained from the application of a multilayer analysis. The effective dielectric constant found with this analysis is $\varepsilon_{\text{eff}} = 7.996$. If the effective dielectric constant is calculated just considering single layer analysis, based in equation (5) of Chapter 2, the effective dielectric constant is equal to $\varepsilon_r = 9.91$. Consequently, the multilayer dielectric analysis provides a result 23.9% lower than the single layer analysis. This result points out the importance of considering multiple layers, since a dielectric 23.9% higher can change analytical results in a significant portion.

Another important result found from the TL equations is the patch input resistance at resonance, which is specified in Table 2. Results show an input resistance of 322 $\Omega$; which is a distant value from 50 $\Omega$ (standard of most feeding lines). This implies that the microstrip patch should need a matching technique when connected to standard 50 $\Omega$ feeding lines. A matching network can be the natural answer; however, it can incur in important device size increment. As was mentioned in Chapters 2 and 3, impedance matching for this antenna can be performed by finding optimal location for CPW. The matching technique is based in equation (35), of Chapter 3, where: $y_0$ is the shorting pin position. Calculations of this technique predict a 50 $\Omega$ matching by placing the shorting pin in an inset position of 155 $\mu$m from the patch radiating edge.

**Table 2: Microstrip patch conductance and input resonant resistance**

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microstrip patch conductance, $G_t [\Omega^{-1}]$</td>
<td>0.0031</td>
</tr>
<tr>
<td>Resonant input resistance, $R_{\text{in}} [\Omega]$</td>
<td>322.58</td>
</tr>
<tr>
<td>Feeding Network inset position for impedance matching, $y_0 [\mu m]$</td>
<td>155</td>
</tr>
</tbody>
</table>

The last important results concerning analytical design are CPW characteristics. A 50 $\Omega$ CPW is desired. The design of the CPW was accomplished by using equations (33) and (34). Table 3 shows the results of CPW design, where $a=55 \mu m$ and $b=125 \mu m$. Variables $a$ and $b$ can be better understood observing Figure 6 in Chapter 2. These dimensions do not exceed the microstrip patch dimensions; as a result feeding line will not introduce size increments to the device because patch and CPW are located in different layers. This result again points out the importance of using multilayer structures.

After the theoretical design of the single patch antenna was performed it is important to test if good predictions were obtained. This will be performed by Momentum simulations, as it is described in the next sections.
Table 3: CPW design, 50Ω characteristic impedance

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPW characteristic Impedance, $Z_{cp} [\Omega]$</td>
<td>50</td>
</tr>
<tr>
<td>$a [\mu m]$</td>
<td>55</td>
</tr>
<tr>
<td>$b [\mu m]$</td>
<td>125</td>
</tr>
</tbody>
</table>

4.1.2 Single patch antenna **Layout, Substrate and simulation setup**

With microstrip patch and CPW dimensions defined, it is possible to develop Momentum simulations. First it is necessary to create a Layout of the antenna. Using the results from analytical design the planar model of the microstrip patch and CPW are created. Figure 17 shows the Layout of the single patch antenna. The Layout development simply relies in drawing desired planar geometries specifying dimensions.

![Figure 17: Layout for single patch antenna, with dimensions specified.](image)

As can be seen in Figure 17, specific dimensions given in Tables 1, 2 and 2 are used. After Layout is completed, it is necessary to define the Substrate characteristics. Figure 18 shows the substrate created for this antenna. In this Substrate one can identify the GaAs, polyimide, Metal 1 and Metal 2 layers. In Figure 18 Metal 1 and Metal 2 are identified as cond and cond2 respectively. The simulations are set to run a Microwave analysis and require port definitions. In this case, three ports are located in the Layout: a feed port for the CPW conductive strip and two ground ports for the CPW ground electrodes.
Figure 18: Momentum Substrate definition for single patch antenna.

Frequencies of analysis are set under the Frequency Plan option in simulation setup. In this case simulations are configured to run from 30 to 40 GHz specifying maximum 50 discrete points. Finally, the last important simulation configuration is related to mesh density. A mesh is simply a group of three-dimensional cells, where the EM calculations are carried out. In general, a larger number of cells in a mesh provide results with higher accuracy. In this case, the number of mesh density is configured to be 20 Cells/Wavelength; because provides enough accuracy, without requiring excessive computer overhead [44].

4.1.3 Simulation results of single patch antenna

The first result obtained from the EM simulations of the single patch antenna is return loss as a function of frequency; which is shown in Figure 19. Resonant frequency for this antenna is located at 33.84 GHz, which is relatively close to analytical design of 35 GHz. This represents a difference of 1.16 GHz, which is a 3% deviation from analytical predictions. This result clearly states that the TL model can provide very good approximations and is useful for basic design purposes. However, it is very important to notice that a difference of 1.16 GHz can be prejudicial in narrow bandwidth systems.

In Figure 19 return loss at resonance has a value of 26.67 dB, which suggest a good impedance matching. However, in order to correctly determine matching characteristics of the antenna it is necessary to analyse VSWR response. Figure 20 shows a plot of VSWR as a function of frequency. There are two important conclusions that can be drawn from Figure 20. First the CPW position found by analytical means provides good approximations to achieve matching, since VSWR is very close to 1 at resonance. A VSWR of 1 implies perfect matching. Second, the antenna does not show very good BW characteristics, which are summarized in Table 4. The fractional BW of this antenna is just 2.57%, which is inside the average for microstrip antennas (1% to 5%) [1]-[7]. This result shows that this antenna is affected by most important limitation of microstrip antennas: their inherent narrow bandwidths.
**Figure 19:** Return Loss as a function of frequency of single patch antenna. Resonant frequency is located at 33.84 GHz with -26.67 dB return loss.

**Figure 20:** VSWR response of single patch antenna. BW is equal to

\[ \Delta f = 0.87 \text{ GHz} \] or \( 2.57\% \).
Table 4: Bandwidth characteristics of single patch antenna

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSWR at resonance</td>
<td>1.097</td>
</tr>
<tr>
<td>VSWR bandwidth [GHz]</td>
<td>0.87</td>
</tr>
<tr>
<td>Fractional bandwidth [%]</td>
<td>2.57</td>
</tr>
</tbody>
</table>

If perfect matching is desired, it is necessary to modify the feeding network position in the single patch antenna. A Smith chart plot of input impedance can be used to find out how the feeding position needs to be changed. Figure 21 shows the input impedance loci of the antenna in a standard Smith Chart. In Figure 21 the VSWR = 2 circle designates the antenna bandwidth. As can be seen, the input impedance at resonance is located slightly to the right of the Smith chart centre, which is the point of ideal matching. This suggests that the antenna input impedance needs to be reduced to achieve matching. Since voltage is maximum at the radiating edges of a microstrip patch, the impedance can be reduced by moving the feeding position towards the centre of the patch [1]- [7].

The only way to find the position of perfect matching is by performing an empirical displacement of the feeding network towards the patch centre. A set of experiments, detailed in Table 5, were conducted to find the position of ideal matching. Feeding position was changed in steps of 10 μm until it was found that the position of perfect matching is located at 185 μm from the patch edge. Figure 22 shows the impedance loci of the antenna with ideal matching.

Analytical design predicted an inset position for matching of 157 μm, which is just 30 μm away from the 185 μm found with a Momentum optimization. This suggests that analytical design based the expression of a coaxial probe position, can provide very good approximations for matching of CPWs with shorting pins. It is also important to notice from Table 5 that: although perfect matching was achieved, resonance frequency was slightly shifted as well. This implies that desirable antenna operation can only be achieved by performing a careful optimization of the structure taking into account both: patch dimensions and feeding position. The next section is devoted to perform an optimization study, in order to find characteristics that would provide 35 GHz operation and make a global comparison with the TL model predictions.
Figure 21: Input impedance loci of single patch antenna. Resonance is located at 33.84 GHz.

Figure 22: Input impedance loci of single patch antenna with perfect matching. Resonance at 34.01 GHz.
Table 5: Empirical study of feeding network inset positions. Steps of 10 μm were used, based in input impedance loci of the antenna.

<table>
<thead>
<tr>
<th>CPW Inset position (y_0) [μm]</th>
<th>VSWR</th>
<th>Resonant Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>155</td>
<td>1.089</td>
<td>33.84</td>
</tr>
<tr>
<td>165</td>
<td>1.045</td>
<td>33.87</td>
</tr>
<tr>
<td>175</td>
<td>1.022</td>
<td>33.94</td>
</tr>
<tr>
<td>185</td>
<td>1.007</td>
<td>34.01</td>
</tr>
</tbody>
</table>

4.1.4 Parametric study for single patch antenna optimization

If it is desired to obtain exact operation at 35GHz and perfect impedance matching, it is necessary to perform an optimization of the antenna in Momentum. This can be achieved by conducting a simple parametric analysis. The resonant frequency found by analytical means is 33.84 GHz; consequently, it is necessary to reduce the patch length. Later, to obtain a perfectly matched antenna it is necessary to modify the feeding network position. The study can be completely performed in two simple steps:

i) Reduce the patch length.
ii) Modify feeding network position until input impedance at resonance is matched.

The patch length is modified in steps of 10 μm, so even small changes in operation can be noticed. The feeding network positions are changed depending if higher or lower impedance are needed for matching. If higher impedance is needed, feeding position has to be moved towards the patch edge, where voltage has a maximum value. On the other hand, if lower impedance is needed, the feeding position has to be moved towards the patch centre [7]. Table 6 shows the results of the parametric study; with the antenna optimized dimensions in the last row. It was possible to achieve operation at 35 GHz, according to the analytical design, with a patch length of 1150 μm. Figure 23 shows a plot of the optimized antenna return loss, where the operation at 35 GHz is shown. Table 7 presents a comparison between the TL model and MoM results.

As can be seen in Table 7, the difference between the antenna length predicted by the TL model and the antenna length optimized with Momentum is just 50 μm; which is an outstanding approximation. The optimized patch length was obtained just with a variation around 4% from predicted values. A similar situation occurs with the resonant frequency, where predicted and optimized values differ just in 1.17 GHz that is a difference of 3.31%. On the other hand, the difference between the predicted feeding position and its optimized counterpart is about 45%; which is a considerable difference. However, the coaxial probe approximation, used to
determine the feeding position, can still be used to provide design insight, because it leads to an easier optimization of the CPW position.

In summary, it was possible to successfully design a single patch antenna, based in the MMIC technology using a CPW feeding. Combining the TL model with Momentum optimizations it was possible to obtain desired results with respect to resonant frequency and impedance matching. Although the TL model was used just to provide a design insight, it offered very accurate predictions. All the results in this section suggest that the approach followed for designing the single patch antenna was successful and can be applied to the development of a dual frequency antenna. In addition, the procedures described can be taken as relatively simple and fast design guidelines, especially considering the fact that detailed antenna design procedures are scarce in the literature.

**Table 6:** Single patch antenna parametric study (optimized parameters for 35GHz operation are shown in the last row)

<table>
<thead>
<tr>
<th>Patch Length, ( L ) [( \mu m )]</th>
<th>CPW Inset position, ( y_0 ) [( \mu m )]</th>
<th>VSWR</th>
<th>Resonant Frequency [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>185</td>
<td>1.007</td>
<td>34.01</td>
</tr>
<tr>
<td>1190</td>
<td>205</td>
<td>1.005</td>
<td>34.30</td>
</tr>
<tr>
<td>1180</td>
<td>215</td>
<td>1.003</td>
<td>34.52</td>
</tr>
<tr>
<td>1170</td>
<td>225</td>
<td>1.009</td>
<td>34.74</td>
</tr>
<tr>
<td>1160</td>
<td>237</td>
<td>1.016</td>
<td>34.96</td>
</tr>
<tr>
<td>1150</td>
<td>223</td>
<td>1.062</td>
<td>35.0</td>
</tr>
</tbody>
</table>

**Table 7:** Comparison between TL model and MoM results of single patch antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TL model</th>
<th>Momentum MoM</th>
<th>Deviation [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch Length, ( L ) [mm]</td>
<td>1.2</td>
<td>1.15</td>
<td>4.167</td>
</tr>
<tr>
<td>Patch Width, ( W ) [mm]</td>
<td>1.6</td>
<td>1.6</td>
<td>-</td>
</tr>
<tr>
<td>CPW Inset position, ( y_0 ) [( \mu m )]</td>
<td>155</td>
<td>225</td>
<td>45.16</td>
</tr>
<tr>
<td>Resonant Frequency [GHz]</td>
<td>33.84</td>
<td>35.01</td>
<td>3.31</td>
</tr>
</tbody>
</table>
Figure 23: Optimized single patch antenna return loss as a function of frequency.

4.2 Dual frequency antenna results

A successful single patch antenna design was achieved and the same procedures are applied for the development of a dual frequency antenna. The dual frequency antenna has the same structure as the single patch antenna, except for a division of the patch in a multiresonator structure, as detailed in Chapter 3. This section is devoted to describe the results obtained from the multiresonator structure and is divided in four parts: the analytical results, momentum simulation setup, simulation results and a parametric study of the dual frequency antenna.

4.2.1 Analytical design of dual frequency antenna

The DFA structure has three resonators: a central fed patch and two parasitically coupled strips. The design of the multiresonator structure consists in determining the dimensions of the three patches, the gaps between them and the CPW position. There are not clear analytical procedures for the design of multiresonator structures in the literature, consequently the dimensions of the structure are found mostly by empirical means combined with the TL equations. It is worth to remember that one of the objectives of the design is to keep the overall size of the DFA around the dimensions of the single patch antenna.

Since it is proposed that the three resonators have the same length, the natural choice for their length is the one found for the single patch antenna: 1.2 mm. Later, the width of every patch has
to be proposed and the resonant frequencies can be found. Given that there are three resonators, the centre patch is proposed to have a width around one third of single patch antenna width. As a reminder, the single patch antenna width was 1.6 mm. A convenient choice for the centre patch width is 0.5 mm, for simple symmetry reasons. A resonant frequency of 46.5 GHz is obtained.

Then, it is necessary to establish the width of the parasitic patches. It is expected to obtain a lower resonant frequency from the parasitic patches, since it is desired to obtain at least one resonant frequency close to the single patch antenna operation. In this way it will be possible to obtain an antenna with similar operation than the single patch antenna, but providing an extra resonant frequency. The size of the parasitic patches is chosen to be 0.6 mm, which is larger than the centre patch and therefore a lower resonant frequency can be obtained. The resonant frequency of the parasitic patches cannot be calculated accurately with TL equations; consequently, the value of the second resonant frequency will be established with Momentum simulations.

The next parameter to establish is the gap size between the centre patch and the parasitic patches. As was said in Chapter 3, it is not possible to determine the size of the gaps by analytical means. Consequently, the procedure suggested in the work of Kumar and Ray [7] is used. It is recommended test gaps around 0.3 times the substrate thickness and run tests until suitable operation is obtained. The substrate thickness is 402 μm including the GaAs substrate and the polyimide layer; consequently the gap that will be used at first has dimensions around 100 μm. In summary, the overall antenna length is 1.2 mm and the overall width is equal to 1.9 mm. This means that the multiresonator width is 0.3 mm larger that the single patch antenna. However, it is important to point out that these values are just used for design reference and an optimization in Momentum will be conducted to reduce the size at maximum.

CPW position is the final design aspect to find. In this case, the coaxial probe approximation is used taking into account just the centre patch. The inset position found is 0.35 mm. Table 8 summarizes the resonator dimensions and CPW inset position used in this structure.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Patch Width, $W$ [mm]</td>
<td>0.5</td>
</tr>
<tr>
<td>Centre Patch Length, $L$ [mm]</td>
<td>1.2</td>
</tr>
<tr>
<td>Parasitic Patches Width, $W$ [mm]</td>
<td>0.6</td>
</tr>
<tr>
<td>Parasitic Patches Length, $L$ [mm]</td>
<td>1.2</td>
</tr>
<tr>
<td>Gap size, $g$ [μm]</td>
<td>100</td>
</tr>
</tbody>
</table>
4.2.2 DFA Layout, Substrate and simulation setup

Once the three patches dimensions and the feeding position are determined, it is possible to develop the Layout of the structure. Figure 24 shows the Layout of the multiresonator antenna, with all the dimensions designated by Table 7. The Substrate definition for this structure is exactly the same as the single patch antenna Substrate in Figure 18. All layer thicknesses and materials are the equal. The simulations again are set as Microwave analysis. The Frequency Plan is configured to run from 30 to 50 GHz specifying 50 discrete points. Finally, the mesh density is set to 20 Cells/Wavelength.

![Figure 24: Multiresonator Layout for dual frequency operation](image)

4.2.3 Simulation results of dual frequency antenna

The structure in Figure 24 was tested in Momentum and the first important result is shown in Figure 25, where the antenna return loss is plotted as a function of frequency. Figure 25 shows that this antenna produces two resonant frequencies, one located at 33.61 GHz and one located at 44.38 GHz. This result confirms that the multiresonator structure, proposed first by Aanandan et al [17]-[19], is able to produce a dual frequency operation using the parasitic coupling principle. This findings are extremely important since they can let to the development of millimetre wave dual frequency antennas, based in a principle as simple as dividing a rectangular patch in several resonators.

Dual frequency operation was successfully achieved by applying theoretical principles of parasitic coupling and TL model, combined with a semi-empirical design approach. Lower
resonant frequency is 10.77 GHz away from the higher one. This is a very interesting result for two reasons. First, an antenna with this operation can be applied in many fields where two far apart resonant frequencies are required, such as some radar and satellite systems. Second, this structure has a lower operation frequency at 33.61 GHz, which is very close to 35 GHz of the single patch antenna. As a result, the antenna offers similar operation to the single patch antenna, but also provides a second resonant frequency.

Although results in Figure 25 confirm dual frequency operation and are extremely interesting; the structure does not show very good performance with respect to return loss and BW. This can be clearly analysed by observing the antenna VSWR response, as is shown in Figure 26. The lower resonant frequency has a return loss of -16.53 dB, while the higher just -5.443 dB. This means that the second resonance is not perceived inside the VSWR BW.

BW corresponding to the lower resonance is 0.81 GHz with a fractional value of 2.4% that is inside the normal range for MSA. But higher resonant response is too low to be perceived. These results clearly state that: although dual frequency operation was accomplished, an optimization is strictly necessary to obtain suitable performance. Next section shows the results of performing an antenna optimization by a parametric study.

![Image of Figure 25: Return loss as a function of frequency for DFA. Lower resonant frequency at 33.61 GHz. Higher resonant frequency at 44.38 GHz.](image-url)
Figure 26: VSWR as a function of frequency for DFA. BW for lower resonance is equal to $\Delta f = 0.81$ GHz. BW for higher resonance is not perceived.

### 4.2.4 Parametric study and optimization of dual frequency operation

In order to understand how DFA operation can be optimized, it is necessary to perform a parametric study concerning four main aspects: centre patch dimensions, parasitic patches dimensions, gap size and CPW position. By conducting a careful analysis of these parameters it is possible to obtain two results: an optimized antenna and a design guide to understand the antenna operation. One of the objectives of the parametric study is to reduce the structure size as much as possible, in order to obtain similar overall size as the single patch antenna.

This study is performed to analyse the influence of the antenna parameters over: resonant frequencies, return loss and VSWR. The starting point of the parametric study is the structure specified in Figure 24; consequently all the parameters are changed around the dimensions shown in this figure. This parametric study follows the premise of changing one parameter while leaving all other characteristics constant. It is desired to test five dimensions larger and five dimensions smaller than the values in Figure 24 for all the parameters. For example, in the case of the centre patch length: five lengths larger than 1.2 mm and five lengths lower than 1.2 mm are tested. Every parameter is changed using a specific step size. For example, the centre patch length is changed in steps of 50 μm, to notice even small variations in operation. Table 9 specifies the step size for all the parameters. Parasitic patches are kept always equal in size.
The results of the complete parametric study are shown in Appendix B, in Tables 12 to 16. In every table three aspects are analysed about both operation frequencies: resonant frequency, return loss and VSWR. The results in Tables 12 to 16 suggest that specific variables are more affected by every parameter. For example, changes in the centre patch length are more influent over the higher resonant frequency. In Tables 12 to 16 the most important effects of each parameter are highlighted in red. Table 10 offers a summary variables controlled by every parameter.

Table 10 offers a guide to control operation variables of the antenna. For instance, if the higher resonant frequency needs to be changed it is necessary to modify the centre patch length. The parasitic patches dimensions control the lower resonant frequency position. This completely agrees with theoretical principles, given that the resonant frequency depends on the patch dimensions. The Gap size has a direct influence on the return loss performance at both resonant frequencies. This occurs because the gap size dictates the intensity of EM coupling. With larger gaps the EM become small. Finally, as expected the inset position of the CPW has influence on the return loss of both operation frequencies. This is because the CPW position controls impedance matching of the antenna. However, it is important to notice that the CPW position has also a significant influence over the higher resonant frequency values. This happens because the CPW not only changes matching, but changes the whole input impedance loci.

**Table 9:** Step size in which every parameter is varied in parametric study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Dimensions [μm]</th>
<th>Step Size [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Patch Length, $L$</td>
<td>1200</td>
<td>50</td>
</tr>
<tr>
<td>Parasitic Patches Length, $L$</td>
<td>1200</td>
<td>50</td>
</tr>
<tr>
<td>Parasitic Patches Width, $W_f$</td>
<td>600</td>
<td>50</td>
</tr>
<tr>
<td>Gap Size, $g$</td>
<td>100</td>
<td>15</td>
</tr>
<tr>
<td>CPW inset position, $y_0$</td>
<td>350</td>
<td>50</td>
</tr>
</tbody>
</table>

**Table 10:** Effects of every parameter on antenna performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Controlled Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Patch Length, $L$</td>
<td>Higher resonant frequency</td>
</tr>
<tr>
<td>Parasitic Patches Length, $L$</td>
<td>Lower resonant frequency</td>
</tr>
<tr>
<td>Parasitic Patches Width, $W_f$</td>
<td>Lower resonant frequency</td>
</tr>
<tr>
<td>Gap Size, $g$</td>
<td>Return Loss in both resonant frequencies</td>
</tr>
<tr>
<td>CPW inset position, $y_0$</td>
<td>Return Loss and Higher resonant frequency</td>
</tr>
</tbody>
</table>
Table 11: Comparison between design and optimized dimensions of DFA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Design Dimensions [μm]</th>
<th>Optimized Dimensions [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre Patch Length, $L$</td>
<td>1200</td>
<td>1150</td>
</tr>
<tr>
<td>Centre Patches Width, $W$</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Parasitic Patches Length, $L_p$</td>
<td>1200</td>
<td>1150</td>
</tr>
<tr>
<td>Parasitic Patches Width, $W_p$</td>
<td>600</td>
<td>500</td>
</tr>
<tr>
<td>Gap Size, $g$</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>CPW inset position, $y_0$</td>
<td>350</td>
<td>550</td>
</tr>
<tr>
<td><strong>Overall planar area [mm$^2$]</strong></td>
<td><strong>2.28</strong></td>
<td><strong>1.84</strong></td>
</tr>
</tbody>
</table>

With the valuable information gathered by the parametric study it was possible to develop an optimized version of the DFA. In this case, optimization means to obtain the minimum size possible with the best performance with respect to return loss and VSWR in both resonant frequencies. Table 11 shows the results of the optimization process and compares them with designed dimensions. As can be seen, the overall area of the antenna was successfully reduced and it is even smaller than the single patch antenna.

Figure 27 shows the return loss and Figure 28 the VSWR of the optimized antenna. In Figure 27 it can be seen that both resonant frequencies have suitable performance with respect to return loss. The resonant frequencies are located at 37.36 GHz and 48.95 GHz, 11.59 GHz apart from each other. This particular operation can be applied in many fields as some radar and satellite systems. Figure 28 shows the VSWR and BW characteristics of the antenna. Both resonant frequencies are very close to perfect matching and BW characteristics are better in comparison to single patch antenna. The lower BW is equal to 3.6%, while the higher bandwidth 2.5%.

In summary it was possible to develop design guidelines to control the operation of the multiresonator DFA. The parametric study provided the means to understand the influence of every parameter on antenna behaviour and lead to the development of optimal dual frequency operation. The analysed multiresonator structure provides a wide number of possibilities regarding practical applications and should be studied in more detail. It is interesting that dual frequency operation can be obtained with a principle as simple as dividing a microstrip patch in several resonators. This antenna proved to be efficient with respect to size considerations. The entire design process in this project successfully confirmed that the combination of various design techniques, such as the use of multilayer structures, CPW feeding and EM coupling, can produce millimetre wave antennas with good performance and compact size.
Figure 27: Return loss as a function of frequency for optimized DFA. The lower resonant frequency is located at 37.36 GHz, while the higher resonant frequency at 48.95 GHz.

Figure 28: VSWR as a function of frequency for optimized DFA. Bandwidth for lower resonance is equal to $\Delta f = 1.37$ GHz or 3.6%. Bandwidth for higher resonance is equal to $\Delta f = 1.22$ GHz or 2.5%.
CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Concluding Remarks

This project addressed the design and simulation of two types of antennas: a single patch antenna and a dual frequency antenna. Both were based in the GaAs MMIC technology and used coplanar waveguide (CPW) feeding. The design process of these antennas involved two steps: analytical design and simulation in Momentum. The analytical design was based in the transmission line (TL) model, while Momentum simulations in the Method of Moments (MoM).

The complete design process led to the successful development of a single patch antenna that works around 35 GHz and a dual frequency antenna that works around 35-50 GHz. Several important conclusions can be drawn from this project.

In first place, it was shown that the TL model provides good approximations concerning antenna dimensions and CPW position. In the case of the single patch antenna, the TL model predicted a patch length of 1.2 mm and width of 1.6 mm for 35 GHz operation. On the other hand, the simulations in Momentum showed a patch length of 1.15 mm and width of 1.6 mm for 35 GHz operation. The difference between both results is just 0.5 mm in length and no difference in width; which clearly confirms that the TL model is an excellent design tool and can be used as starting point for patch design. Regarding CPW inset position, the TL model predicted 155 μm and Momentum 225 μm. In this case, the difference is more notorious; but the TL model can still be used to provide design insight. It is very important to remember that good analytical approximations were achieved because multilayer considerations were applied to find the effective dielectric constant due to fringing fields.

The combination of the TL model equations with a subsequent optimization in Momentum led to the development of a single patch antenna operating exactly at 35GHz. A detailed design was developed, even considering special characteristics of the antenna such as: multilayer structure and CPW feeding. This shows that the procedures followed can be used as a design guide for similar antennas. As careful design procedures are scarce in the literature, this project can be used as a starting point for further investigation regarding millimetre wave antennas with similar characteristics. Furthermore, the design of the single patch antenna led to an easier design of the dual frequency antenna.

A dual frequency antenna operating around 35-50 GHz was successfully designed combining the TL model and empirical manipulations in Momentum. The most important finding is that dual frequency operation was achieved by using a simple principle: divide a microstrip patch in
several multiresonators. The most significant advantage of this antenna is that size enlargement is not required to produce two resonant frequencies. The technique used in this work is more efficient, in terms of size, compared to other multi frequency techniques such as: stacked patch antennas, parasitic elements coupled to a main patch and the use of shorting pins or diodes. In addition, the relative simplicity and symmetry of this antenna suggests a feasible manufacture in practical conditions. The use of a multiresonator structure for dual frequency operation, combined with MMICs and CPW, has not been reported before and represents a totally novel design.

The use of a multilayer MMIC structure provided the great advantage of size reduction in both antennas. By locating the radiating elements and feeding network in different layers it was possible to reduce planar size. The use of CPW showed that it is possible to obtain impedance matching just adjusting feeding position, without extra matching networks. This implies that CPW is extremely efficient and can lead to significant device size reduction. In summary the use of MMIC technology and CPW in antennas provide very efficient designs.

The last important conclusion is that Momentum is an extremely powerful and useful tool for antenna design. Both antennas were developed with a relatively simple procedure that included the creation of Layout, Substrate and simulation setup. By using Momentum it was possible to optimize both antennas and create a detailed parametric study of the dual frequency antenna. The parametric study comprises an interesting design guide that can be used in future research to explore the possibilities offered by the multiresonator structure. It is important to notice that predictions offered by Momentum can be directly applied to the manufacture of antennas, given that the MoM have shown a great level of accuracy with respect to experimental operation.

5.2 Recommendations for future research

The findings of this project open a wide number of possibilities for future research regarding the dual frequency antenna. In first place, it was shown that this antenna suffers from the most important limitation of microstrip antennas: short bandwidth. As a consequence, extensive research can be devoted to increase the bandwidth of this antenna. Another important limitation of the design is the lack of a clear theoretical model to be used as design guide. Some models, based in the EM coupling of microstrip lines have been applied to explain this antennas, nevertheless, without providing design procedures [17]-[19]. Modelling of the multiresonator structure can be a main topic for future research. Finally, an interesting possibility is the exploration of multi frequency operation by dividing the antenna in more than three resonators, as was done in this project. Multi frequency operation can be applied to a great number of applications in the present [9], [20]-[24].
REFERENCES


%Code created to calculate the patch dimensions of MSA
%Author: Jorge Moreno
%Year: 2016
%The University of Manchester
%References: [1]-[7], [40]

clear

% Constants and other defined parameters

c=3E8; % speed of light in vacuum [m/s]
er1=12.85; %Relative Electrical permittivity of GaAs
er2=3.5; %Relative Electrical permittivity of first polyimide
er3=1; %Relative Electrical permittivity of air
fr=35E9; % Resonant frequency [Hz]
h1=400E-6; % Substrate Thickness [m]
h12=402E-6; % Substrate + First Polyimide Thickness [m]
h13=402E-6; % Substrate + First Polyimide + Third Layer (Air in this case)

% Microstrip patch width determination [m]
W=(c/(2*fr))*sqrt(2/(er1+1)); %patch width

%Effective Dielectric Constant determination. Multilayer structure
We=W+((2*h12)/pi)*log(17.08*((W/(2*h12))+0.92)); %Effective width [m]
ve=((2*h12)/pi)*atan((2*pi/((pi*We)-(4*h12)))*(h13-h12));

q1=(h1/(2*h12))*(1+(pi/4)-
((h12/We)*log(((2*We/h1)*sin(pi*h1)/(2*h12))+cos((pi*h1)/(2*h12)))));
q2=1-q1-(h12/(2*We))*log((pi*We/(2*h12)-1));
q3=1-q1-q2-(((h12-ve)/(2*We)))*log(((2*We)/(2*h13-
h12+ve))*(pi*ve)/(2*h12))+(sin((pi*ve)/(2*h12)));

er=(er1*er2*((q1+q2)^2)/((er1*er2)+(er2*er1)))+er3*((1-q1-q2)^2)/((er3*(1-q1-q2-q3)+q3)); % Multilayer effective dielectric constant

%Patch length determination
Delta_L=h12/sqrt(ere); % Length extension due to fringing [m]
L=(c/(2*fr*sqrt(ere)))-(2*Delta_L); % Microstrip patch length [mm]
L_eff=L+(2*Delta_L); % Effective length due to fringing effects [m]
A.2 CPW characteristic impedance and position

%Code created to calculate the input impedance of a microstrip patch, CPW characteristic impedance and position.
%Author: Jorge Moreno
%Year: 2016
%The University of Manchester
%References: [1]-[7], [29]-[35]

clear

e0=8.854187717E-12; % Electrical permittivity of vacuum [F/m]
er=12.5; %Relative Electrical permittivity of GaAs
c=3E8; % speed of light in vacuum [m/s]
fr=35E9; % Resonant frequency [Hz]
h=400E-6; % Substrate Thickness [m]
lambda0=c./fr; %Free space Wavelength [m]
k0=(2*pi)./lambda0; %Free space Wave number [rad/m]

W=500E-6; % Patch Width
L=1.2E-3; % Patch Length

G=(W./(120*lambda0)).*(1-((1/24)*((k0*h).^2))); % Conductance of radiating patch [siemens]

Gt=2*G; % Total patch conductance
R1=1/Gt; % Input resistance at radiating edge

% Feed position
y0=(L/pi)*asin(sqrt(50/R1)); % Coaxial probe approximation

%%Characteristic Impedance of CPW Finite Thickness and Finite Ground Planes
a=55E-6; %distance from middle point of conductive strip to edge of conductive strip
b=125E-6; %distance from middle point of conductive strip to edge of ground electrode
k3=a/b*sqrt((1-((b*b)/(c*c)))/(1-((a*a)/(c*c))));
k3square=k3^2;
kk3=sqrt(1-(k3square));
K3=(pi)/log(2*((1+sqrt(kk3))/(1-sqrt(kk3)))); % Eliptic function for 0<k<2<0.5

k4=(sinh((pi*a)/(2*h))/sinh((pi*b)/(2*h)))*sqrt((1-(((sinh((pi*b)/(2*h)))^2)/((sinh((pi*c)/(2*h)))^2)))/(1-(((sinh((pi*a)/(2*h)))^2)/((sinh((pi*c)/(2*h)))^2))));
kk4=sqrt(1-(k4^2));
K4=(pi)/log(2*((1+sqrt(kk4))/(1-sqrt(kk4)))); % Eliptic function for 0<k<2<0.5

er_eff3=1+((er-1)/2)*(K4/K3); % effective dielectric constant
ZoCPWf=((30*pi)/sqrt(er_eff3))*1/K3; % CPW characteristic impedance
APPENDIX B: PARAMETRIC STUDY OF DUAL FREQUENCY ANTENNA

B.1 Parametric study results of length of the centre patch

Table 12: Parametric study of Centre Patch Length; the most important effects of the parameter are highlighted in red

<table>
<thead>
<tr>
<th>Number of Test</th>
<th>Centre Patch Length [μm]</th>
<th>Lower Operation Frequency</th>
<th>Higher Operation Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>950</td>
<td>33.69</td>
<td>-24.32</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>33.69</td>
<td>-20.69</td>
</tr>
<tr>
<td>3</td>
<td>1050</td>
<td>33.65</td>
<td>-20.50</td>
</tr>
<tr>
<td>4</td>
<td>1100</td>
<td>33.65</td>
<td>-16.89</td>
</tr>
<tr>
<td>5</td>
<td>1150</td>
<td>33.63</td>
<td>-15.91</td>
</tr>
<tr>
<td>Design Values</td>
<td>1200</td>
<td>33.61</td>
<td>-16.53</td>
</tr>
<tr>
<td>1</td>
<td>1250</td>
<td>33.63</td>
<td>-14.92</td>
</tr>
<tr>
<td>2</td>
<td>1300</td>
<td>33.65</td>
<td>-14.79</td>
</tr>
<tr>
<td>3</td>
<td>1350</td>
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</tr>
<tr>
<td>5</td>
<td>1450</td>
<td>33.66</td>
<td>-15.85</td>
</tr>
</tbody>
</table>
### B.2 Parametric study results of parasitic patches length

**Table 13:** Parametric study of Parasitic Patches Length; the most important effects of the parameter are highlighted in red

<table>
<thead>
<tr>
<th>Number of Test</th>
<th>Parasitic Patches Length [μm]</th>
<th>Lower Operation Frequency</th>
<th>Higher Operation Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>950</td>
<td>38.67</td>
<td>-15.90</td>
</tr>
<tr>
<td>2</td>
<td>1000</td>
<td>37.57</td>
<td>-13.99</td>
</tr>
<tr>
<td>3</td>
<td>1050</td>
<td>36.59</td>
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</tr>
<tr>
<td>4</td>
<td>1100</td>
<td>35.48</td>
<td>-13.31</td>
</tr>
<tr>
<td>5</td>
<td>1150</td>
<td>34.61</td>
<td>-14.08</td>
</tr>
<tr>
<td></td>
<td>Design Values</td>
<td>1200</td>
<td><strong>-16.53</strong></td>
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<td>1</td>
<td>1250</td>
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<td>-</td>
</tr>
<tr>
<td>2</td>
<td>1300</td>
<td>31.97</td>
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<td>3</td>
<td>1350</td>
<td>31.26</td>
<td>-27.52</td>
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<tr>
<td>4</td>
<td>1400</td>
<td>30.52</td>
<td>-32.22</td>
</tr>
<tr>
<td>5</td>
<td>1450</td>
<td>29.92</td>
<td>-24.66</td>
</tr>
</tbody>
</table>
## B.3 Parametric study results of parasitic patches width

**Table 14:** Parametric study of Parasitic Patches Width; the most important effects of the parameter are highlighted in red

<table>
<thead>
<tr>
<th>Number of Test</th>
<th>Parasitic Patches Width [μm]</th>
<th>Lower Operation Frequency</th>
<th>Higher Operation Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>350</td>
<td>35.50</td>
<td>-19.19</td>
</tr>
<tr>
<td>2</td>
<td>400</td>
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</tr>
<tr>
<td>3</td>
<td>450</td>
<td>34.64</td>
<td>-17.13</td>
</tr>
<tr>
<td>4</td>
<td>500</td>
<td>34.29</td>
<td>-16.40</td>
</tr>
<tr>
<td>5</td>
<td>550</td>
<td>33.94</td>
<td>-16.12</td>
</tr>
<tr>
<td><strong>Design Values</strong></td>
<td><strong>600</strong></td>
<td><strong>33.61</strong></td>
<td><strong>-16.53</strong></td>
</tr>
<tr>
<td>1</td>
<td>650</td>
<td>33.33</td>
<td>-14.99</td>
</tr>
<tr>
<td>2</td>
<td>700</td>
<td>33.09</td>
<td>-14.41</td>
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<td>3</td>
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<td>800</td>
<td>32.55</td>
<td>-13.73</td>
</tr>
<tr>
<td>5</td>
<td>850</td>
<td>32.34</td>
<td>-13.39</td>
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</tbody>
</table>
B.4 Parametric study results of length of gap size

Table 15: Parametric study of Gap Size; the most important effects of the parameter are highlighted in red

<table>
<thead>
<tr>
<th>Number of Test</th>
<th>Gap Size [μm]</th>
<th>Lower Operation Frequency</th>
<th>Higher Operation Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>34.42</td>
<td>-25.087</td>
</tr>
<tr>
<td>2</td>
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<td>3</td>
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<td>4</td>
<td>70</td>
<td>33.85</td>
<td>-17.39</td>
</tr>
<tr>
<td>5</td>
<td>85</td>
<td>33.72</td>
<td>-16.25</td>
</tr>
<tr>
<td>Design Values</td>
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<td>33.61</td>
<td><strong>-16.53</strong></td>
</tr>
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<td>1</td>
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<td>33.43</td>
<td>-13.84</td>
</tr>
<tr>
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<td>145</td>
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<td>-12.87</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>33.25</td>
<td>-11.99</td>
</tr>
<tr>
<td>5</td>
<td>175</td>
<td>33.16</td>
<td>-11.49</td>
</tr>
</tbody>
</table>
### B.5 Parametric study results of length of CPW inset position

**Table 16:** Parametric study of CPW inset position; the most important effects of the parameter are highlighted in red

<table>
<thead>
<tr>
<th>Number of Test</th>
<th>CPW inset position [μm]</th>
<th>Lower Operation Frequency</th>
<th>Higher Operation Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>32.51</td>
<td>-9.91</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>32.64</td>
<td>-10.55</td>
</tr>
<tr>
<td>3</td>
<td>200</td>
<td>32.99</td>
<td>-11.06</td>
</tr>
<tr>
<td>4</td>
<td>250</td>
<td>33.07</td>
<td>-12.21</td>
</tr>
<tr>
<td>5</td>
<td>300</td>
<td>33.46</td>
<td>-13.33</td>
</tr>
</tbody>
</table>

| Design Values | 350                      | 33.61                     | -16.53           | 1.35 | 44.38                     | -5.44            | 3.29 |
| 1              | 400                      | 33.98                     | -17.29           | 1.32 | 45.04                     | -6.11            | 2.96 |
| 2              | 450                      | 34.20                     | -24.56           | 1.18 | 45.64                     | -6.98            | 2.62 |
| 3              | 500                      | 34.61                     | -27.59           | 1.09 | 46.46                     | -8.39            | 2.23 |
| 4              | 550                      | 34.84                     | -34.39           | 1.04 | 47.18                     | -11.43           | 1.73 |
| 5              | 600                      | -                         | -                | -    | -                         | -                | -    |
APPENDIX C: FEASIBILITY STUDY

Design, Modelling and Simulation of Compact Antennas Using Multilayer GaAs MMICs

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ABSTRACT

Monolithic microwave integrated circuits (MMIC), based on gallium arsenide (GaAs) technology, have drawn the attention of industry and researchers during the past decades due to interesting characteristics such as low cost, small size and reliability. In addition, it has been demonstrated that GaAs MMICs can provide the means to accomplish the integration of entire transceivers in a single chip, due to their high miniaturization potential. This project addresses the design, modelling and simulation of compact multilayer antennas based on the GaAs MMIC technology. In specific, it is desired to explore the effects of geometry changes and different feeding network structures on the overall performance of MMIC antennas. For this, several sets of simulations are conducted using the 3D electromagnetic planar simulator Momentum. This project aims to compare and contrast results with respect to past publications in order to generate possible novel ideas.
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1. INTRODUCTION

Monolithic microwave integrated circuits (MMIC), based on gallium arsenide (GaAs) technology, are being widely applied in the fabrication of antennas and waveguides due to their great advantages over other MIC technologies [1], [2]. Some of the important advantages of GaAs MMIC technology are: low cost, high miniaturization potential, stability and good broadband performance [3]. Additionally, it has been demonstrated that GaAs MMICs can provide the means to accomplish the integration of entire transceivers in a single chip [1].

This project addresses the design, modelling and simulation of compact multilayer antennas based on the GaAs MMIC technology. The study is divided into two main sections: a) The design and geometry optimization of several multilayer patch antennas, to find desired characteristics with respect to bandwidth, resonant frequency and insertion loss b) The test of different coplanar waveguide (CPW) feeding networks to explore effects in electromagnetic (EM) coupling and impedance values. Two software platforms will be used to develop the entire study: The 3D EM planar simulator Momentum, which is integrated to Keysight Advanced Design System (ADS), and the high level computing language/environment MATLAB. Momentum is used to design, model and develop EM simulations for the antennas; while MATLAB is used for performing calculations and graph generation.

1.1 AIM AND OBJECTIVES

The main aim of this work is to design, model and simulate 3D MMIC antennas, based on the previous results of references [1], [2] and [10], in order to find desired characteristics with respect to bandwidth, resonant frequency and insertion loss. From the main aim of the study, three objectives are directly derived:

i) Modify the geometric characteristics of the antenna radiating patches to explore effects on resonant frequency, bandwidth and input return loss magnitude.

ii) Test a number of feeding network positions, relative to antenna radiating elements, to study possible changes in impedance, bandwidth and resonant frequency.

iii) Explore several CPW structures to obtain specific feeding network impedances and analyse the effects of unintentional EM coupling.
1.2 BACKGROUND AND THEORY

This section briefly summarizes the most relevant theoretical principles and background needed to understand the design procedure of the GaAs MMIC compact antennas. In addition, definitions about the different software packages used through the simulations are given for a better comprehension of their characteristics.

1.2.1 Microstrip antennas

The necessity of microstrip antennas have increased significantly in the past few decades due to their importance in applications such as mobile, satellite and aircraft communications. Microstrip antennas are low profile, small in size, lightweight and inexpensive to manufacture. A microstrip antenna is composed by a very thin metallic strip or patch, a dielectric material called substrate and a ground plane. Figure 1 shows the generic structure of a planar microstrip antenna. The metallic patch is the radiating element and depending on the excitation mode, it can behave as a broadside or end-fire radiator [6].

![Figure 1: Microstrip antenna structure [6]](image)

There are several materials currently used for the substrate of microstrip antennas, depending on the desired antenna characteristics. Usually, thick substrates with low dielectric constants provide antennas with good efficiency and bandwidth characteristics; however, leading to larger device sizes. On the other hand, thin substrates with high dielectric constants can be used to produce smaller devices [6].

The radiating patch of a microstrip antenna may also have several geometric characteristics depending on the desired antenna performance. The most common patch shapes are square, rectangular, circular and elliptical, among others. However, square and rectangular patches are more widely used, because of their ease of fabrication and analysis [6]. Microstrip antennas are also known as patch antennas and

5
will be referred as that along this study. It is also important to mention that microstrip antenna arrays are extensively used to achieve determined radiation patterns and improve directivity, in comparison with single antenna elements [6].

There are several models and methods used to analyse patch antennas; however, the most widely used are: the transmission line, cavity and the full wave models. The transmission line and the cavity models have relative simplicity and can give good physical insight; however, they have difficulties for modelling coupling. On the other hand, the full wave model is more complex, but it is more accurate and versatile [6]. In this work, the designed antennas are analysed using the 3D planar EM simulator Momentum, which is based on the full wave model [7]. Patch antennas are going to be designed using the 3D-MMIC technology, which in contrast to the planar configuration of Figure 1, is based on a multilayer architecture as will be discussed in a latter section.

1.2.2 Antenna feeding network: Coplanar Waveguide

There are several feeding techniques for microstrip antennas, which can be divided into two main groups: contacting and non-contacting feeding. As their name implies contacting feeding networks are directly connected to the radiating antenna patch. Examples of contacting feeding networks are the microstrip lines (like the one in Figure 1) strip lines and coaxial probes. On the other hand, non-contacting networks provide feeding to the radiating element via EM coupling [6].

In both, contacting and non-contacting feeding networks the most popular structures are the microstrip lines. However, typical microstrip lines show a direct dependence between their characteristic impedance and the substrate thickness. This creates a number of difficulties for the use of materials with high dielectric constant; which is a major constrain in modern MICs, where size is the key factor. Moreover, microstrip lines are not very efficient for shunt connections, given that their ground plane is located in the opposite side of the substrate. All these microstrip line disadvantages and limitations led to the creation of an alternative feeding network: the coplanar waveguide (CPW) [8].

A CPW is composed by a thin metallic strip placed in between of two parallel ground electrodes. In a CPW all the conducting elements are located on the same plane, which is a great advantage in comparison with common microstrip lines. Figure 2 depicts the structure of a generic CPW, where 2a is the centre strip width and 2b corresponds to the distance between the ground planes [8]. The structure of the CPW allows easy shunt connections between components and it is also ideal for MMIC
interconnections. In addition, the characteristic impedance of a CPW does not show a strong dependence on the substrate thickness [8]. Those attributes are the main reasons why CPW have been widely applied as feeding networks in the development of MMIC antennas [1]. During this study all the designed antennas rely on CPW structures as feeding networks.

![CPW Structure](image)

**Figure 2: CPW structure [8]**

### 1.2.3 GaAs 3D-MMIC antennas

Three dimensional (3D) MMIC technology has drawn the attention of industry and researchers during the past decades because it offers interesting characteristics such as low production cost, small size and high reliability [3]. In 3D-MMIC technology the distinct elements of a microwave circuit or system, passive and active, are grown over a substrate [4]. The main difference between 3D-MMIC and other microwave integrated circuit technologies is that it relies in a multilayer architecture instead of a planar structure; thus reducing the device size and manufacture costs [1], [5].

The MMICs studied in this work have a GaAs semi-insulating thick substrate, which has an electrical permittivity of 12.85 [1], [3]. GaAs is widely used in modern MMICs because of its high electrical permittivity and mostly because it exhibits carrier mobilities than can be six times faster than Si. These characteristics turn GaAs into an excellent choice for microwave and millimetre wave applications [9].

Figure 3 shows the structure of a multilayer patch antenna, which offers a clear view of the MMIC concept. In the antenna of Figure 3 the feeding network and the radiating elements are located in different layers; showing the great advantage of MMIC technology over conventional planar structures with respect to the use of space [1]. The MMIC antenna in Figure 3 comprises five layers grown over a
GaAs substrate. There are three metallic layers, corresponding to the CPW feeding network and a lower and upper microstrip patches. The other two layers are made of dielectric polymides [1]. This particular structure is going to be used through this work, based on the results of previous publications in references [1], [2] and [10]. The objective is to modify several characteristics of this antenna structure, such as patch geometry and CPW, to explore the specific effects on antenna performance and behaviour.

1.2.4 ADS Momentum

Momentum is a 3D planar EM simulator from Keysight Technologies. Momentum is a powerful software platform that provides the necessary tools for the design of devices and components for a wide range of applications, such as MMIC, RF, RFIC and Signal Integrity. The EM simulator Momentum is integrated into Keysight ADS and other interesting platforms like Cadence Virtuoso; which allows the parallel design of ICs, packages and boards for high frequency applications [7].

ADS Momentum uses the Method of Moments (MoM) for EM calculation, which is a very accurate numerical technique based in the integral form of Maxwell’s equations. This means that this software is capable to provide advanced and highly detailed EM simulations of the desired devices. In addition, Momentum provides visualization of surface currents and planar antenna radiation, founded on detailed S-parameter description; which is the most important feature for antenna design [6], [7]. In this project ADS Momentum, is used to perform the whole design and electromagnetic analysis for the GaAs MMIC antennas.

Figure 3: Multilayer patch antenna structure [1], [10].
1.2.5 MATLAB

MATLAB is one of the most used software platform in engineering and science around the world. MATLAB integrates at the same time a high level programming language and an environment for data analysis, graph visualization and algorithm development. This software offers an extremely wide range of application fields such as signal processing, control systems design, computational biology, etc. [11]. In this work the MATLAB environment is used for possible numerical calculations, regarding the antennas design, and for graph generation. MATLAB provides very interesting features for graph visualization that will be extensively explored through this project.

2. LITERATURE REVIEW

There is a very important amount of research conducted over the topics of patch antennas and CPW; however, in terms of MMIC technology these topics seem to be relatively new and not extensively explored yet [3]. This project is exclusively focused on the GaAs MMIC technology for antenna applications and is especially committed to compare results with past publications. These are the reasons why the literature review in this work is condensed into three main topics: multilayer patch antennas, CPW in MMIC technology and geometry optimization of MMIC patch antennas.

2.1 GaAs Multilayer Patch Antennas

In recent years the interest for GaAs MMIC technology has increased significantly, mainly because they have shown excellent results for the design of multiband antennas. Reference [1] reports the design and manufacture of several multiband MMIC antennas operating around 35 GHz. The publication in reference [1] is concerned with the bandwidth, resonant frequency and radiation patterns obtained from the several studied antennas. The structure used for the MMIC antennas is similar to the one in Figure 3, in which the device is defined to have five layers over the substrate [1].

In reference [1], the substrate is a 400-μm-thick GaAs layer, while the polymide layers have a thickness of 2 μm. There are three metallic layers identified from bottom to top as metals 1, 2 and 3. The metallic layers are 1 μm, 1 μm and 3 μm thick respectively. Three different antennas were tested using the generic structure in Figure 3: two single patch antennas (in metals 2 and 3), a stacked patch antenna (using metals 2 and 3) and a spur line antenna (in metal 2). It is very important to notice that the feeding network every case corresponds to a CPW located in the metal 1 layer [1]. The structure and layer thickness used in reference [1] are the starting points for the antenna design during this project.
Reference [1] mentions that the patches in metals 2 and 3 are concentrated. It is said that making the top patch slightly smaller, it is possible to achieve impedance equalization. Additionally, reference [1] mentions that introducing a small offset on the relative position of the antenna patches it is possible to increase the bandwidth due to coupling effects [1]. Those geometric considerations are going to be studied in detail during the design of the MMIC antennas in this project, as is mentioned in the objectives of section 1.1. This is the reason why results will be directly compared with reference [1].

It is also worth to mention that reference [1] uses the MoM for the EM analysis of the antennas. The study is concerned with a boundary problem for the unknown surface current. Equation (1) expresses the boundary problem as an integral equation [1].

\[
E^e_I(r) = Z_s J_S(r) + j\omega \int_S G_A(r|r') J_S(r') d'S - \frac{1}{j\omega} \Delta t \int_S G_V(r|r') \Delta t J_S(r') d'S \quad (1)
\]

Where \(E^e_I\) the electric field incident to the conductive surfaces, \(J_S\) is the surface current, \(G_A\) is a 3D dyadic Green’s function, \(G_V\) is a Green’s function related to the voltage and \(Z_s\) is the surface impedance of the patches [1]. Equation (1) is used to find the surface current and with some additional adjustments it also can be used to find the far field patterns of the antennas [1]. It is important to consider equation (1), since it can be the first stage for understand the analysis and simulations of the MMIC antennas in this project.

Several important results were found in reference [1] with respect to bandwidth, resonant frequencies and radiation patterns of the antennas. All results are presented as return loss and radiation patterns graphs. For illustration purposes the results for the stacked patch antenna are reproduced in Figure 4 [1]. From these results it was found that the stacked patch antenna exhibits bandwidths of 3.5% and 1.67% in the lower (35.65 GHz) and upper (38.9 GHz) resonant frequencies respectively. Also, it can be easily noticed that the simulated and measured results differ in an important proportion. Reference [1] explains the important deviation from simulated results as a problem associated with software assumptions; which is a main constrain to consider. It is also mentioned that an undesired notch at 30GHz is produced due to the superstrate (polymide) layer [1]. The scheme of analysis and graph presentation of reference [1] is going to be widely used during this project.
2.2 CPW in multilayer MMIC

As was mentioned in section 1.2.2 CPW have several advantages over other feeding networks and their use in MMICs is very popular in the present. One of the objectives of this work is to explore the effects of CPW characteristics over the antennas performance; that is the reason to explore previous works related to CPW configurations. One of the most interesting publications regarding CPW in MMIC technologies is offered by reference [2]. The work in reference [2] is especially concerned with the comparison between several CPW MMIC structures, to observe their different impedance and EM coupling characteristics. Reference [2] presents the simulation and fabrication of the CPW structures shown in Figure 5 [2].
As can be seen from Figure 5, the CPW analysed in reference [2] are based on GaAs technology and are designed as MMICs. The CPW in Figure 5 have a multilayer structure corresponding to the GaAs substrate, two polymide layers and a number of metallic layers that depend on the particular structure. Reference [2] studies the characteristics of every structure in terms of impedance, dissipation loss and EM coupling. The characteristic impedance and the dissipation loss of the CPWs are examined with respect to their S-parameter characterization. The characteristic impedance of a CPW is given by equation (2) and the dissipation loss by equation (3) [2].

\[
Z_0 = Z_{sys} \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \quad (2)
\]

\[
Loss = 10 \log \frac{1 - |S_{11}|^2}{|S_{21}|^2} \quad (3)
\]

Where \(Z_0\) is the characteristics impedance, \(Z_{sys}\) is the system impedance which in general is 50 \(\Omega\) [2]. Equations (2) and (3) are especially important for the design of the MMIC antennas in this work, since they are going to be used extensively to study CPWs. It is important to mention that reference [2] uses ADS Momentum for performing simulations; consequently results can be directly compared.

According to the results in reference [2] a V-shape structure, like the one in a2) of Figure 5, is able to reduce the characteristic impedance with respect to the common planar structure of a1). On the other
hand, the elevated structures in b1) and b2) increase the impedance values. Reference [2] also found that overlaps between metallic layers can reduce significantly the impedance with strong dependence on the overlap width. Input return losses are directly connected with the impedance values [2]. The entire set of results of reference [2] is very important for this work, since they open the possibilities for studies concerning CPW structures in MMIC antennas. In this project it is desired to explore the effects of using different CPW structures on the antennas performance and behaviour, especially with respect to impedance and EM coupling.

2.3 MMIC antenna geometry optimization

One of the most important concerns of several publications regarding MMIC antennas is the optimization of geometric and structural characteristics to improve performance [10]. In reference [1] it is said that the relative size and position of multilayer patches can achieve impedance equalization, resonance frequency control and even extend the bandwidth. Another interesting example of geometry modification is given in reference [10], where an Artificial Neural Network (ANN) is developed to obtain optimized characteristics with respect to the patch size. Reference [10] uses the same antenna structure shown in Figure 3 and develops a study that is concerned with the reduction of the patch size, without affecting resonant frequency and bandwidth. By the formulation of an ANN with complex mathematical background, reference [10] is able to reduce the upper and lower patch size in an important proportion.

The results in references [1] and [10] are extremely important for the purposes of this project since they set parameters of comparisons for the MMIC antenna design in this project. If the results of references [1] and [10] are combined with the conclusions of reference [2], where several CPW structures are explored, it is possible to develop a very interesting study concerning the characteristics of GaAs MMIC antennas. This approach can produce a very complete analysis with respect to MMIC antennas performance in dependence of geometry and specific CPW structures. This project aims to compare and contrast possible findings with respect to these past publications in order to generate possible novel ideas.

3. METHODOLOGY

This project has a simulation approach; consequently its entire experimental development relies on computational tools. The experimental procedure is divided into two main stages: the antenna design
and the implementation of the EM simulations. During the antenna design the specific structure, dimensions and material characteristics of the antennas will be defined. In addition, the different antennas models will be created, taking into account the different geometries and structures to be studied. On the other hand, during the simulation stage the distinct EM analysis are defined. Also, the specific parameters of study, such as input return loss, dissipation loss, impedance and radiation patterns, are determined in the simulation stage.

3.1 Antenna Design

As was mentioned in section 1.1, there are three main objectives in this project concerned with geometry and structural changes of the antennas. Consequently three different set of experiments are going to be conducted, each one directly related to one objective. The general structure of Figure 3 is the starting point of all the experiments and is going to be modified through the study. The antennas analysed in this work will have a GaAs substrate, two polymide layers and three metallic layers. Two metallic layers will correspond to the antenna patches and one to the CPW feeding network.

The first objective in this project is concerned with the geometry modification of the antenna patches in order to find effects on bandwidth, resonance frequency and return loss magnitude. For this, three antennas with different upper and lower path sizes are going to be compared in terms of performance; based on the previous results of reference [10]. For these three antennas, the feeding network will be defined to be the same. A CPW with ordinary planar structure is going to be used. The specific patch sizes will be defined after a careful literature review.

The second objective of this work corresponds to test different feeding network positions, relative to the antenna patches. In this case a set of three antennas, with the same upper and lower patch sizes are tested. CPW with planar structure are going to be located in different positions in the three cases. The effects on impedance and bandwidth due to coupling effects are analysed.

Finally, the last objective of this project is to explore the effects of using different CPW structures in the antennas. In this case, a set of six different antennas, with the same upper and lower patch size are studied. All the CPW structures defined in Figure 5 are going to the tested in the MMIC antenna. It is important to notice that, due to the modification of the CPW structure, the whole antenna will suffer configuration changes in comparison with the other two sets of experiments.

3.2 EM Simulations and Parameters of Analysis
Once the three set of experiments of the project were defined, it is necessary to determine the characteristics of the simulations and parameters of analysis for each one. As was mentioned in section 1.2.4, ADS Momentum is based on the full wave method. Consequently, the simulations obtained from Momentum are very accurate and can give a complete description of the antennas performance. The simulations carried out in Momentum are able to give descriptions in terms of S-parameters, radiation patterns and impedances. The same simulations, based on MoM and visualization of surface currents are applied to the three sets of experiments [7]. However the parameters extracted in each one are different.

For the first set of experiments, corresponding to the antenna patch size modification, the parameters analysed will be the input return loss and radiation patterns. From these parameters bandwidth and resonance frequency characteristics can be found. In the case of the second set of experiments, concerned with the feeding network position, the parameters to analyse will be the input return loss, radiation patterns and impedance values. Finally, for the third set of experiments, which considers different CPW structures, the parameters of analysis will be the dissipation loss, the impedance and the EM coupling measure between two elements given by $S_{21}$. All the graphs and possible calculations related to the simulation results will be processed with MATLAB. Figure 6 shows a hierarchy graph that summarizes the whole experimental procedure of the project. First, the antennas are designed for the three different experimental sets, then the same kind of simulations are conducted for the three groups and finally different parameters of analysis are extracted for each set.

### 4. PROJECT PLANNING

This project comprises four main steps: intensive literature review, design of MMIC antennas, simulation execution and results analysis. In addition it is necessary to consider the report writing, which is going to be conducted through almost the entire duration of the project. Table 1 shows a detailed schedule of activities for the whole project, expressed as a Gantt chart. Table 2 shows the specific calendar dates corresponding to the weeks in the Gantt chart of Table 1.
Figure 6: Hierarchy diagram defining the project methodology and parameters of analysis.
Table 1: Gantt chart for project planning.

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<td>Experimental Set 1 (patch size): EM simulations in ADS Momentum</td>
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<td>Result analysis for the three sets of experiments</td>
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<td>Overall experimental analysis and conclusions</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Dissertation report writing</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>
Table 2: Specific calendar dates for the weeks in Table 1.

<table>
<thead>
<tr>
<th>Week Number</th>
<th>Specific Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>29th April - 1st May</td>
</tr>
<tr>
<td>2</td>
<td>2nd May - 8th May</td>
</tr>
<tr>
<td>3</td>
<td>9th May - 15th May</td>
</tr>
<tr>
<td>4</td>
<td>13th June - 19th June</td>
</tr>
<tr>
<td>5</td>
<td>20th June - 26th June</td>
</tr>
<tr>
<td>6</td>
<td>27th June - 3rd July</td>
</tr>
<tr>
<td>7</td>
<td>4th July - 10th July</td>
</tr>
<tr>
<td>8</td>
<td>11th July - 17th July</td>
</tr>
<tr>
<td>9</td>
<td>18th July - 24th July</td>
</tr>
<tr>
<td>10</td>
<td>25th July - 31th July</td>
</tr>
<tr>
<td>11</td>
<td>1st August - 7th August</td>
</tr>
<tr>
<td>12</td>
<td>8th August - 14th August</td>
</tr>
<tr>
<td>13</td>
<td>15th August - 21th August</td>
</tr>
<tr>
<td>14</td>
<td>22th August - 28th August</td>
</tr>
<tr>
<td>15</td>
<td>29th August - 4th Sept.</td>
</tr>
</tbody>
</table>

5. RISK ASSESSMENT

The design and simulation of the MMIC antennas in this work is entirely developed on software platforms, consequently all the tasks correspond to computer use in The University of Manchester computer clusters and also in off campus facilities. This is why possible risks, that may affect the project completion, are mostly concerned with software availability and correct operation. In this sense, the most important action to be taken is a pre-evaluation of the locations where the software can be accessed and also the acquisition of a licence for off campus usage. Also it would be important to find out if the available software versions are updated.

The health and safety risk assessment in this project is mostly associated with computer and display screen equipment (DSE) work. Consequently, the health and safety risk evaluation considers possible physical effects caused by long term computer and DSE manipulation. The risk assessment form in
Appendix A gives a summary of the possible risks and all the actions proposed to mitigate health problems related to computer/DSE work [12].

6. CONCLUSION

GaAs MMIC technology offers a very wide range advantages over other MIC technologies, as a consequence it is very important to explore its principles and characteristics. This project is committed to analyse in detail several attributes of GaAs MMICs technology applied to the antenna design. Using simulation means it will be possible to explore the behaviour and possible performance improvements of MMIC antennas. The comparison of results with past works can produce possible novel ideas related to GaAs MMIC antennas.
7. REFERENCES


# APPENDIX A

## HEALTH AND SAFETY RISK ASSESSMENT

### General Risk Assessment Form

<table>
<thead>
<tr>
<th>Date:</th>
<th>Assessed by:</th>
<th>Checked by:</th>
<th>Location:</th>
<th>Assessment ref no</th>
<th>Review date:</th>
</tr>
</thead>
<tbody>
<tr>
<td>12/05/2016</td>
<td>Jorge Moreno</td>
<td>Prof. Ali Rezazadeh</td>
<td>Any Computer Cluster or Laboratory</td>
<td></td>
<td>Constantly</td>
</tr>
</tbody>
</table>

**Task / premises:** Common computer use, Display Screen Equipment (DSE) work.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Hazard</th>
<th>Who might be harmed and how</th>
<th>Existing measures to control risk</th>
<th>Risk rating</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Computer use</td>
<td>Possible general body aches and pain</td>
<td>Person performing computer work.</td>
<td>Correct adjustment of workstation, including chair, computer screen and mouse. Constant short breaks.</td>
<td>LOW</td>
<td>T</td>
</tr>
<tr>
<td>DSE work</td>
<td>Possible eye fatigue and headache.</td>
<td>Person performing computer work.</td>
<td>Correct configuration of screen brightness and contrast. Constant short breaks.</td>
<td>LOW</td>
<td>T</td>
</tr>
</tbody>
</table>

**Result:** $T =$ trivial, $A =$ adequately controlled, $N =$ not adequately controlled, action required, $U =$ unknown risk

*University risk assessment form and guidance notes.*

*Revised Aug07*
<table>
<thead>
<tr>
<th>Ref No</th>
<th>Further action required</th>
<th>Action by whom</th>
<th>Action by when</th>
<th>Done</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Computer use</td>
<td>Correct adjustment of workstation, including chair, computer screen and mouse. Constant short breaks.</td>
<td>Person performing computer work.</td>
<td>Constantly</td>
<td>Constantly</td>
</tr>
<tr>
<td>2. DSE work</td>
<td>Correct configuration of screen brightness and contrast. Constant short breaks.</td>
<td>Person performing computer work.</td>
<td>Constantly</td>
<td>Constantly</td>
</tr>
</tbody>
</table>
APPENDIX B

RECORD OF MEETINGS WITH SUPERVISOR

MSc Feasibility Study Supervision Record

<table>
<thead>
<tr>
<th>Student Name:</th>
<th>Jorge Moreno</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student ID:</td>
<td>9600911</td>
</tr>
<tr>
<td>Supervisor:</td>
<td>Prof. Ali Rezaadhe</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Meeting Number</th>
<th>Date</th>
<th>Tuttee</th>
<th>Supervisor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>26/09/16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>06/05/16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>11/05/16</td>
<td></td>
<td>E-mail Meeting</td>
</tr>
</tbody>
</table>

Signatures