ACTIVE MICROSTRIP ARRAY ANTENNAS

by

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Submitted for the degree of Bachelor of Engineering (Honours)
in the division of Electrical and Electronic Engineering

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Dear Professor Simmons,

In accordance with the requirements of the degree of Bachelor of Engineering (Honours) in the division of Electrical and Electronic Engineering, I present the following thesis entitled “Active Microstrip Array Antennas”. This work was performed under the supervision of Associate Professor Marek E. Bialkowski.

I declare that the work submitted in this thesis is my own, except as acknowledged in the text and footnotes, and has not been previously submitted for a degree at the University of Queensland or any other institution.

Yours faithfully

Chin Liong Yeo
To my family
Acknowledgements

I wish to thank and acknowledge Associate Professor Marek E. Bialkowski for his time and patience in guiding me during the course of this thesis. Without his invaluable advises and assistance, the completion of this thesis would not be possible. In addition, I would also like to express my appreciation and lots of thanks to Mr Hyok J. Song for his assistance in answering many of my queries. Last but not least, special thanks to Mr Damian G. Jones and Mr Richard R. Taylor for their assistance for the use of the facilities at the microwave laboratory.
Abstract

This thesis is concerned with investigations of two types of broadband antenna elements that are to be used for spatial power combining. The first antenna is the Linearly Tapered Slot Antenna (LTSA) while the second is the Uniplanar Quasi-Yagi antenna. Both these antennas are to be fabricated with a high dielectric constant substrate material (Duriod with dielectric constant $\varepsilon_r = 10.2$), substrate thickness of 0.635mm and design frequency of 12.5GHz.

The first part of the thesis deals with the theory behind microstrip antennas and transmission lines. An introduction to microstrip antennas is presented, followed by a literature review on microstrip design equations and background information with regard to microstrip broadband planar antennas. The three most commonly used broadband planar antennas are illustrated, namely the Microstrip Patch antenna, Quasi-Yagi antenna and Tapered Slot Antenna. In contrast to the microstrip patch, both the LTSA and the Quasi-Yagi antenna radiates at the end-fire direction. As a result, both these antennas can achieve higher gain, lower side lobes and wider bandwidth compared to the conventional microstrip patch antenna. The second part of the thesis is concerned with design procedures and considerations for both the antennas. The designs for the two antennas are aimed at obtaining wider bandwidth and better radiation patterns. In addition, a sensitivity analysis of the Quasi-Yagi antenna with respect to five design parameters is demonstrated in chapter 6 of this thesis. The simulation of the Quasi-Yagi is accomplished by using a commercially available full-wave (MoM) method of moment analysis software package IE3D of Zeland Software Inc.

The simulation results showed that the Quasi-Yagi antenna is able to achieve a simulated 36% frequency bandwidth for voltage standing-wave ratio VSWR < 2 at the centre frequency of 12.5GHz. During the sensitivity analysis, it has been found that the most sensitive parameters are the length of the driver, director and the distance from the driver to the reflector. Variations to these three parameters will affect the antenna’s performance in terms of return loss and operational frequency.
# Contents

Acknowledgement  vii  
Abstract  viii  
Contents  xii  
List of Figures  xv  
List of Tables

## 1 Introduction

1.1 Importance 1  
1.2 Aim of Thesis 2  
1.3 Outline of Thesis 2

## 2 Theory

2.1 Microstrip Transmission Line 5  
2.1.1 Basic Microstrip Line 6  
2.1.2 Microstrip Field Radiation 7  
2.1.3 Substrate Materials 8  
2.2 The Microstrip Antenna 11  
2.2.1 Historical Development 11  
2.2.2 Basic Microstrip Antenna 12  
2.2.3 Radiated Fields of Microstrip Antenna 13
4.2.2 Advantages and Disadvantages of Quasi-Yagi Antenna 40

4.3 Microstrip Tapered Slot Antennas 41
4.3.1 Types of Tapered Slot Antenna 41
4.3.2 Definition of E-plane and H-plane for TSAs 43
4.3.3 Advantages and Disadvantages of Tapered Slot Antenna 43

4.4 Spatial Power Combining 44

5 Design and Development of Microstrip Broadband Planar Antennas 47

5.1 Design of Uniplanar Quasi-Yagi Antenna 48
5.1.1 Design Considerations 48
5.1.2 Antenna Dimensions 49

5.2 Design of Linearly Tapered Slot Antenna 53
5.2.1 Design Considerations 53
5.2.2 Antenna Dimensions 54

6 Results and Discussion 57

6.1 Sensitivity Analysis of Quasi-Yagi Antenna 58
6.1.1 Length of Director 59
6.1.2 Distance Between Director and Driver 60
6.1.3 Distance Between Coupled Microstrip Lines 62
6.1.4 Length of Driver 64
6.1.5 Distance From the Driver to the Reflector 65
6.1.6 Final Design 67

6.2 Simulation Results of Quasi-Yagi Antenna 68
6.2.1 S11 Return Loss and Bandwidth 68
6.2.2 Voltage Standing-Wave Ratio 69
6.2.3 Impedance Smith Chart and Average Current Density 70
6.2.4 Radiation Patterns of Quasi-Yagi Antenna 72

7 Summary and Future Prospects 75

7.1 Summary 75

7.2 Future Prospects 77

References 79
List of Figures

2.1 Structure of microstrip transmission line 6
2.2 Electromagnetic field pattern of a microstrip 7
2.3 Basic configuration of microstrip antenna 12
2.4 Microstrip antenna and coordinate system 13
2.5 Various patch patterns used for microstrip patch antenna 17
2.6 Microstrip traveling-wave antennas 18
2.7 Microstrip slot antennas 19
2.8 Microstrip line fed antennas 21
2.9 Coaxial fed microstrip antennas 22
3.1 Extremely wide ($w >> h$) and extremely narrow ($w << h$) microstrip lines 24
3.2 Characteristic impedance versus $w/h$ for microstrip with $\varepsilon_r$ as parameter 29
3.3 Effective dielectric constant and normalized guide wavelength of microstrip versus $w/h$ with $\varepsilon_r$ as parameter 29
3.4 Comparison of impedance characteristics of microstrip, suspended microstrip and inverted microstrip. $\varepsilon_r=3.78$ 30
3.5 Various types of microstrip discontinuities 31
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Planar antenna selection chart</td>
<td>34</td>
</tr>
<tr>
<td>4.2</td>
<td>Broadside radiation direction of microstrip patch antenna</td>
<td>35</td>
</tr>
<tr>
<td>4.3</td>
<td>Microstrip aperture coupled patch antenna</td>
<td>36</td>
</tr>
<tr>
<td>4.4</td>
<td>Microstrip patch antenna array configurations</td>
<td>37</td>
</tr>
<tr>
<td>4.5</td>
<td>Uniplanar Quasi-Yagi antenna</td>
<td>39</td>
</tr>
<tr>
<td>4.6</td>
<td>End-fire radiation direction of Quasi-Yagi antenna</td>
<td>39</td>
</tr>
<tr>
<td>4.7</td>
<td>Different types of end-fire Tapered Slot Antenna</td>
<td>41</td>
</tr>
<tr>
<td>4.8</td>
<td>End-fire radiation pattern of Tapered Slot Antenna</td>
<td>42</td>
</tr>
<tr>
<td>4.9</td>
<td>Definition of E- and H- planes for TSAs</td>
<td>43</td>
</tr>
<tr>
<td>4.10</td>
<td>Four system configurations of circuit and spatial approaches</td>
<td>45</td>
</tr>
<tr>
<td>4.11</td>
<td>Spatially-Fed/Spatially-Combined approach</td>
<td>46</td>
</tr>
<tr>
<td>5.1</td>
<td>Schematic diagram of Quasi-Yagi Antenna</td>
<td>50</td>
</tr>
<tr>
<td>5.2</td>
<td>Actual size of Quasi-Yagi Antenna</td>
<td>53</td>
</tr>
<tr>
<td>5.3</td>
<td>Different sections of the LTSA</td>
<td>54</td>
</tr>
<tr>
<td>5.4</td>
<td>Top and bottom metalization of LTSA</td>
<td>55</td>
</tr>
<tr>
<td>6.1</td>
<td>Investigated parameters of the Quasi-Yagi antenna</td>
<td>58</td>
</tr>
</tbody>
</table>
6.2 Schematic diagram of Quasi-Yagi antenna from IE3D

6.3 $S_{11}$ return loss of Quasi-Yagi Antenna

6.4 Simulated VSWR of the Quasi-Yagi Antenna

6.5 Impedance smith chart of Quasi-Yagi Antenna

6.6 Average current density at 12.5GHz

6.7 2D polar pattern of Quasi-Yagi Antenna

6.8 2D radiation pattern of Quasi-Yagi Antenna

6.9 3D radiation pattern of Quasi-Yagi Antenna

6.10 3D mapped pattern of Quasi-Yagi Antenna
List of Tables

2.1 Properties of microwave dielectric substrates ................................................. 10

2.2 Typical properties of RT/Duriod microwave materials ............................................ 10
CHAPTER 1

INTRODUCTION

This chapter highlights the importance of active array antennas to the present day communication world. After defining the aim of this thesis, chapter one closes with an overview of the thesis, listing a brief summary of the topics discussed in all of the chapters of this thesis.

1.1 Importance

Communication can be broadly defined as the transfer of information from one point to another. A communication system is usually required when the information is to be conveyed over a distance. The transfer of information within the communication system is commonly achieved by superimposing or modulating the information onto an electromagnetic wave which acts as a carrier for the information signal. At the required destination, the modulated carrier is then received and the original information signal
can be recovered by demodulation. Over the years, sophisticated techniques have been developed for this process using electromagnetic carrier waves operating at radio frequencies as well as microwave and millimeter wave frequencies.

In today’s modern communication industry, antennas are the most important components required to create a communication link. Through the years, microstrip antenna structures are the most common option used to realize millimeter wave monolithic integrated circuits for microwave, radar and communication purposes. Due to its many advantages over the conventional antenna, the microstrip antenna have achieved importance and generated interest to antenna designers for many years. In fact, active microstrip antenna arrays and active apertures are increasingly present in phased-array radar applications. In addition, these devices also serve as potentially efficient power combiners. Hence, active microstrip antennas arrays are often used in spatial or “quasi-optical” combining schemes for creating high-power and high-frequency components. Furthermore, microstrip antennas are often used in military aircraft, missiles, rockets and satellites.

1.2 Aim of Thesis

The aim of this thesis is to investigate two types of broadband antenna elements that are to be used as an antenna array in spatial power combining. The first type of antenna is the Linearly Tapered Slot Antenna (LTSA) and the second type is the Uniplanar Quasi-Yagi antenna. Both antennas will be designed at the operating frequency of 12.5Ghz using a high dielectric constant material Duroid (dielectric constant $\varepsilon_r = 10.2$) with substrate thickness of 0.635mm.

1.3 Outline of Thesis

Chapter 1 begins with the importance of active array antennas to the communications industry. Both the significance and the applications of the active microstrip array antennas are given. Moreover, the aim of the thesis is also listed.
Chapter 2 will review the background information and theory of microstrip antennas. General characteristics and basic antenna theory will be discussed in this chapter. The historical development of the microstrip antenna, including its advantages and disadvantages, are presented. In addition, different types of substrate materials used for microstrip antennas are mentioned. Lastly, the three types of microstrip antennas are listed, followed by two excitation techniques commonly used to feed microstrip antennas.

Chapter 3 will provide a literature review relating to the design of the microstrip antenna. The design formulas for calculating the effective dielectric constant, free-space wavelength, guide wavelength and characteristic impedance are all listed accordingly. After giving an explanation of the synthesis equations developed by Wheeler, the microstrip relationship plots for the characteristic impedance and effective dielectric constant versus w/h are given. This chapter ends with an analysis of microstrip discontinuities, listing all the various common discontinuities found in microstrip antenna designs.

Chapter 4 will give background information of microstrip broadband planar antennas. The three most commonly used broadband planar antennas, namely the Microstrip Patch antenna, Quasi-Yagi antenna and Tapered Slot Antenna, will be analyzed. The individual characteristics of the three types of antenna will be presented, including the advantages and disadvantages of these three types of antenna structures. The chapter ends with a brief explanation on spatial power combing and four possible power-combining architectures.

Chapter 5 concentrates on the design and development of two kinds of microstrip broadband planar antennas, the Quasi-Yagi antenna and the Linearly Tapered Slot antenna. The design procedures involved in obtaining the dimensions for both the antennas will be shown in detail. The aim of the design is to obtain wider bandwidth and better radiation patterns for both the antennas. In addition, other design considerations like the geometry parameters and the materials selected for the antenna are also presented.
Chapter 6 provides all simulated results related to the Quasi-Yagi antenna. A sensitivity analysis of the Quasi-Yagi antenna with respect to five design parameters; the length of the director, distance between the director and the driver, distance between the coupled microstrip lines, length of the driver and distance from the driver to the reflector, will be shown. The effects of the five parameters on its operational frequency and impedance bandwidth are investigated and the parameters most affecting the performance of the antenna are identified. Additionally, the radiation patterns and parameters generated by the antenna are shown.

Chapter 7 concludes this thesis with a summary of the work carried out for this thesis and the future prospects for both the Quasi-Yagi antenna and the Linearly Tapered Slot antenna. A overview of the topics covered in this thesis will be displayed. Subsequently, the future prospects of microstrip antennas, especially broadband planar antennas, will be addressed.
CHAPTER 2

THEORY

This chapter provides background information regarding the basic microstrip transmission line. The basic geometry of the microstrip line is illustrated, followed by an analysis of the microstrip electromagnetic field pattern. Furthermore, the different types of substrate materials used for microstrip antennas are listed. After presenting the historical development, the advantages and disadvantages of the microstrip antenna, a listing of the three various categories of microstrip antenna will be discussed, specifically the microstrip patch antenna, microstrip traveling-wave antenna and microstrip slot antenna. Finally, the chapter ends with the excitation techniques used to excite microstrip antennas.
2.1 Microstrip Transmission Line

2.1.1 Basic Microstrip Line

The microstrip line is most commonly used as microwave integrated circuit transmission medium. Microstrip transmission line is a kind of "high grade" printed circuit construction, consisting of a track of copper or other conductor on an insulating substrate. There is a "backplane" on the other side of the insulating substrate, formed from a similar conductor. Basically, it comprised of a metal strip supported above a larger dielectric material and a ground plane. Looking at the cross-section of the microstrip transmission line, the track on top of the substrate will serve as a "hot" conductor, whereas the backplane on the bottom serves as a "return" conductor. Microstrip can therefore be considered a variant of a 2-wire transmission line.

![Fig 2.1: Structure of Microstrip Transmission Line](image)

The general geometry of microstrip antenna is shown in figure 2.1 as above. The most important dimensional parameters in microstrip circuit design are the width $w$ and height $h$ (equivalent to the thickness of the substrate) [1]. Another important parameter is the relative permittivity of the substrate ($\varepsilon_r$). The thickness of the metallic, top-conducting strip $t$ and conductivity $\sigma$ are generally of much lesser importance and may be often neglected. The metallic strip is usually printed on a microwave substrate material.
2.1.2 Microstrip Field Radiation

If one solves the electromagnetic equations to find the field distributions, one will tend to find very nearly a completely TEM (transverse electromagnetic) pattern. This means that there are only a few regions in which there is a component of electric or magnetic field in the direction of wave propagation. The field pattern is commonly referred to as a Quasi-TEM pattern. Shown in figure 2.2 is the electromagnetic field pattern of the basic microstrip transmission line.

![Electromagnetic Field Pattern of a Microstrip](image)

Under some conditions, one has to take into account of the effects due to longitudinal fields. An example is geometrical dispersion, where different wave frequencies travel at different phase velocities, and the group and phase velocities are different. The difference between microstrip transmission line and stripline is that the microstrip is a homogenous transmission line. This means that the electromagnetic fields are not entirely contained in the substrate. Hence, microstrip line cannot support pure TEM mode of transmission, as phase velocities would be different in the air and the substrate [2]. Instead, a quasi-TEM mode is established. The quasi-TEM pattern arises because of
the interface between the dielectric substrate and the surrounding air. The electric field lines have a discontinuity in direction at the interface. The boundary conditions for electric field are that the normal component (i.e. the component at right angles to the surface) of the electric field times the dielectric constant is continuous across the boundary; thus in the dielectric which may have dielectric constant 10, the electric field suddenly drops to 1/10 of its value in air. On the other hand, the tangential component (parallel to the interface) of the electric field is continuous across the boundary. In general, a sudden change of direction of electric field lines at the interface is observed, which gives rise to a longitudinal magnetic field component from the second Maxwell's equation, \( \text{curl } E = - \frac{dB}{dt} \). Since some of the electric energy is stored in the air and some in the dielectric, the effective dielectric constant for the waves on the transmission line will lie somewhere between that of the air and that of the dielectric. Typically the effective dielectric constant will be 50-85% of the substrate dielectric constant. Since the microstrip structure is not uniform, it will support the quasi-TEM mode.

### 2.1.3 Substrate Materials

The choice of substrate used is an important factor in the design of a microstrip antenna. Important qualities of the dielectric substrate include:

- The microwave dielectric constant
- The frequency dependence of this dielectric constant which gives rise to "material dispersion" in which the wave velocity is frequency-dependent
- The surface finish and flatness
- The dielectric loss tangent, or imaginary part of the dielectric constant, which sets the dielectric loss
- The cost
- The thermal expansion and conductivity
- The dimensional stability with time
- The surface adhesion properties for the conductor coatings
- The manufacturability (ease of cutting, shaping, and drilling)
- The porosity (for high vacuum applications)
Since the substrate dimensions and dielectric constant are functions of substrate temperature, the operating temperature range becomes an important property in the design of any microstrip antenna. In addition, the dielectric constant and loss tangent are also functions of frequency. As for physical properties which is important in fabrication of the antenna, they are resistance to chemicals, tensile and structural strengths, flexibility, machinability, impact resistance, strain relief, formability, bondability and substrate characteristics when clad.

Generally, there are two types of substrates used: soft and hard substrates [2]. Soft substrates are flexible, cheap and can be fabricated easily. However, it possesses higher thermal expansion coefficients. Typical examples of soft substrates are RT Duriod 5870 ($\varepsilon_r = 2.3$), RT Duriod 5880 ($\varepsilon_r = 2.2$) and RT Duriod 6010.5 ($\varepsilon_r = 10.5$). As for hard substrates, it has better reliability and lower thermal expansion coefficients. On the other hand, it is more expensive and non-flexible. Typical examples of hard substrates are quartz ($\varepsilon_r = 3.8$), alumina ($\varepsilon_r = 9.7$), sapphire ($\varepsilon_r = 11.7$) and Gallium Arsenide GaAs ($\varepsilon_r = 12.3$).

There are numerous substrates that can be used for the design of microstrip antennas, with their dielectric constants usually in the range of $2.2 \leq \varepsilon_r \leq 12$. The low dielectric constant $\varepsilon_r$ is about 2.2 to 3, the medium around 6.15 and the high approximately above 10.5. Normally, thick substrates with low dielectric constants are often used as it provides better efficiency, larger bandwidth and loosely bound fields for radiation into space. However, it would also result in a larger antenna size. On the other hand, using thin substrates with higher dielectric constants would result in smaller antenna size. The drawbacks are that it is less efficient and has relatively smaller bandwidths. Therefore, there must be a design trade-off between the antenna size and good antenna performance [3].
Tables 2.1 and 2.2 below show the properties of some common substrate materials.

### Table 2.1: Properties of Microwave Dielectric Substrates

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative Dielectric Constant</th>
<th>Loss Tangent at 10 GHz (tan δ)</th>
<th>Thermal Conductivity K (W/cm·°C)</th>
<th>Dielectric Strength (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sapphire</td>
<td>11.7</td>
<td>10^{-4}</td>
<td>0.4</td>
<td>4 × 10^3</td>
</tr>
<tr>
<td>Alumina</td>
<td>9.7</td>
<td>2 × 10^{-4}</td>
<td>0.3</td>
<td>4 × 10^3</td>
</tr>
<tr>
<td>Quartz (fused)</td>
<td>3.8</td>
<td>10^{-4}</td>
<td>0.01</td>
<td>10 × 10^3</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>2.53</td>
<td>4.7 × 10^{-4}</td>
<td>0.0015</td>
<td>280</td>
</tr>
<tr>
<td>Beryllium oxide (BeO)</td>
<td>5.6</td>
<td>10^{-4}</td>
<td>2.5</td>
<td>—</td>
</tr>
<tr>
<td>GaAs</td>
<td>12.3</td>
<td>16 × 10^{-4}</td>
<td>0.3</td>
<td>350</td>
</tr>
<tr>
<td>(p = 10^{-7} Ω · cm) SI</td>
<td>11.7</td>
<td>50 × 10^{-4}</td>
<td>0.9</td>
<td>300</td>
</tr>
<tr>
<td>3M 250 type GX</td>
<td>2.5</td>
<td>19 × 10^{-4}</td>
<td>0.0026</td>
<td>200</td>
</tr>
<tr>
<td>Keene DI-clad 527</td>
<td>2.5</td>
<td>19 × 10^{-4}</td>
<td>0.0026</td>
<td>200</td>
</tr>
<tr>
<td>RT Duriod 5870</td>
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<td>12 × 10^{-4}</td>
<td>0.0026</td>
<td>200</td>
</tr>
<tr>
<td>3M Cu-clad 233</td>
<td>2.33</td>
<td>12 × 10^{-4}</td>
<td>0.0026</td>
<td>200</td>
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<tr>
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<td>12 × 10^{-4}</td>
<td>0.0026</td>
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<td>0.0026</td>
<td>200</td>
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<td>3M Clad 5217</td>
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<td>9 × 10^{-4}</td>
<td>0.0026</td>
<td>200</td>
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<tr>
<td>Keene DI-clad 880</td>
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<td>9 × 10^{-4}</td>
<td>0.0026</td>
<td>200</td>
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<tr>
<td>RT Duriod 6010</td>
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<td>0.004</td>
<td>160</td>
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<tr>
<td>3M epilam 10</td>
<td>10.2</td>
<td>15 × 10^{-4}</td>
<td>0.004</td>
<td>160</td>
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<tr>
<td>Keene DI-clad 810</td>
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<td>15 × 10^{-4}</td>
<td>0.004</td>
<td>160</td>
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<tr>
<td>Air</td>
<td>1.0</td>
<td>0</td>
<td>0.00024</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2.2: Typical Properties of RT/Duriod Microwave Materials
2.2 The Microstrip Antenna

Microstrip antennas are a new and exciting technology. In fact, the microstrip antenna can now be considered an established type of antenna that is confidently used by designers worldwide, especially when low-profile radiators are required.

2.2.1 Historical Development

The concept of microstrip antennas was first proposed by Deschamps [4] as early as 1953, Gutton and Bassinot [5] in 1955. However, not much carry-on researches have been carried out until 1972. Since then, it took about twenty years before the first practical microstrip antennas were fabricated in the early 1970's by Munson [6] and Howell [7]. Howell first presented the design procedures for microstrip antennas whereas Munson tried to develop microstrip antennas as low-profile flushed-mounted antennas on rockets and missiles. In addition, research publications regarding the development of microstrip antennas were also published by Bahl and Bhartia [3] and James, Hall and Wood [8]. Dubost had also published a research monograph which covers more specialized and innovative microstrip developments. In fact, all these publications are still in use today.

In October 1979, the first international meeting devoted to microstrip antenna materials, practical designs, array configurations and theoretical models was held at New Mexico State University under co-sponsorship of the U.S. Army Research Office and New Mexico State University’s Physical Science Laboratory [9], [10]. In 1979, Hall reported the design idea of electromagnetically coupled patch antenna and proved experimentally that it is able to possess higher bandwidth while maintaining a simple fabrication process [11].

The early 1980’s was not only a crucial point in publications but also a milestone in practical realism and manufacturing of the microstrip antennas [12]. Present-day system requirements are an important factor in the development of printed antennas. Since then,
antenna researchers began to take an interest in ‘antenna array architecture’, which has emerged as a dominant approach to the microstrip world.

2.2.2 Basic Microstrip Antenna

In today’s aircraft and spacecraft applications where the antenna’s size, weight, cost, performance, ease of installation and aerodynamic profile are of utmost consideration, the low-profile microstrip antenna is preferred over conventional antennas. The term ‘microstrip’ actually refers to any type of open wave guiding structure which is not only a transmission line but also used together with other circuit components like filters, couplers, resonators, etc. In fact, microstrip antennas are an extension of the microstrip transmission line. Microstrip antennas can be flush-mounted to metal or other existing surfaces, and they only require space for the feed line, which is usually placed behind the ground plane. As for its disadvantages, microstrip antennas are inefficient and possess very narrow frequency bandwidth, typically only a fraction of a percent or at most a few percent. A microstrip antenna in its simplest configuration consists of a radiating patch on one side of a dielectric substrate, which has a ground plane on the other side. The patch conductors, usually made of copper or gold, can be virtually assumed to be of any shape. However, conventional shapes are normally used to simplify analysis and performance prediction. The radiating elements and the feed lines are usually photoetched on the dielectric substrate.

![Figure 2.3: Basic Configuration of Microstrip Antenna](image)
Shown in figure 2.3 is the basic configuration of a simple microstrip antenna. The upper surface of the dielectric substrate supports the printed conducting strip while the conducting ground plane backs the entire lower surface of the substrate. The radiating patch may be square, rectangular, circular, elliptical or any other configurations. Square, rectangular and circular shapes are the most common because of the ease of analysis and fabrication. As for the feed line, it is also a conducting strip, normally of a smaller width. Coaxial-line feeds, where the inner conductor of the coax is attached to the radiating patch, are also widely used. Sometimes, microstrip antennas are also referred as printed antennas.

2.2.3 Radiated Fields of Microstrip Antenna

![Microstrip Antenna and Coordinate System](image)

Figure 2.4: Microstrip Antenna and Coordinate System
The field structure within the substrate and between the radiating element and the ground plane is shown in figures 2.4(a) and 2.4(b). The electromagnetic wave traveling along the microstrip feed line spreads out under the patch. Hence, the resulting reflections at the open circuit set a standing-wave pattern. From figure 2.4(b), it can be clearly seen that the radiated fields undergo a phase reversal along the length of the structure, but is approximately uniform along the width of the structure.

The antenna consists of two slots, separated by a very low impedance parallel-plate transmission line which acts as a transformer [2]. The length of the transmission line has to be approximately $\lambda_g/2$ in order for the fields at the aperture of the two slots to have opposite polarization. The components of the field from each slot add in phase and provide a maximum radiation normal to the element. As for the electric field at the aperture of each slot, it can be categorized into x and y components, as shown in figure 2.4(c). The y components are out of phase and hence, their contributions will cancel out each other.

Due to the fact that the thickness of the microstrip is normally very small, the electromagnetic waves generated within the dielectric substrate (between the patch and the ground plane) undergo considerable reflections when they arrive at the edge of the strip. Hence, only a small fraction of the incident energy is radiated. As a result, the antenna is considered to be very inefficient and it behaves more like a cavity instead of a radiator.

2.2.4 Advantages vs. Disadvantages of Microstrip Antennas

The attractiveness of the microstrip antenna method stems from the idea of making use of printed circuit technology. Due to the fact that the microstrip antenna’s structure is planar in its configurations, it is able to enjoy all the advantages of a printed circuit board with all of the power dividers, matching networks, phasing circuits and radiators. In addition, as the backside of the microstrip antenna is a metal ground plane, the antenna can be directly placed onto a metallic surface of an aircraft or missile.
Moreover, microstrip antennas have several advantages compared to conventional microwave antennas and therefore, it can accommodate many applications over the broad frequency range from 100 MHz to 50 GHz. Some of the outstanding advantages of the microstrip antennas compared to conventional microwave antennas are [3]:

- Light in weight, small in size, low profile planar configurations which can be made conformal
- Low fabrication cost, suitable for mass production
- Can be made thin so that the aerodynamics of any aerospace vehicles would not be affected
- Can be easily mounted onto missiles, rockets and satellites without much alterations
- Low scattering cross section
- Possible to achieve linear, circular (left hand or right hand) polarizations with simple changes in feed position
- Easy to obtain dual frequency operations
- Requires no cavity backing
- Compatible with modular designs (solid state devices such as oscillators, amplifiers, variable attenuators, switches, modulators, mixers, phase shifters, etc. can be added directly to the antenna substrate board)
- Feed line and matching networks are fabricated all together with antenna structure

Nevertheless, the disadvantages of the microstrip antennas are:

- Small bandwidth ~ 0.5 to 10%
- Lower gain
- Most microstrip antennas radiate into a half plane
- Practical limitations on the maximum gain (~ 20dB)
- Poor end-fire radiation performance
- Poor isolation between feed lines and radiating elements
- Possibility of excitation of surface waves
• Lower power handling capability

There are methods of significantly reducing the effect of some of the above-mentioned disadvantages. For example, efficiency and bandwidth of microstrip antennas can be improved by increasing the height of the substrate [13]. However, increasing the height of the substrate will also introduce surface waves. Surface waves are not desirable, as it would affect the antenna pattern and polarization characteristics. Thus, in order to maintain the large bandwidth as well as to eliminate the surface waves, it is necessary to use cavities.

2.2.5 Applications

After analyzing the advantages and disadvantages of the microstrip antennas, it can be observed that its advantages significantly overshadow its disadvantages. Due to the fact that most present-day systems demand for small size, lightweight, low cost and low profile antennas, the employment of microstrip technology arises extensively over the years. Even though conventional antennas possess far superior performance over microstrip antennas, it is still clearly disadvantaged by the other properties of the microstrip antennas. Microstrip antennas are particularly suited to those applications where low profile antennas are required. The reason is because it can conform to a given shape easily. With continuing research and development and increased usage of the microstrip antenna, it is expected that they will ultimately replace conventional antennas for most applications. Shown below are some typical system applications which employ microstrip technology [3]:

• Satellite communications
• Doppler and other radars
• Radio altimeter
• Command and control
• Missile telemetry
• Weapon fuzing
• Manpack equipment
2.3 Types of Microstrip Antennas

Microstrip antennas can be differentiated by more physical parameters than any conventional microwave antennas. In fact, microstrip antennas may be of any geometrical shape and any dimension. However, the three basic categories of all microstrip antennas are: microstrip patch antennas, microstrip traveling-wave antennas and microstrip slot antennas. The following sections will briefly describe the basic characteristics of all the three antennas.

2.3.1 Microstrip Patch Antennas

![Various patch patterns used for Microstrip Patch Antenna](image)

Figure 2.5: Various patch patterns used for Microstrip Patch Antenna
A microstrip patch antenna consists of a conducting patch of any planar geometry on one side of a dielectric substrate with a ground plane on the other side. There are practically an unlimited number of patch patterns for which radiation characteristics may be calculated. Shown in figure 2.5 are the various patch patterns used for microstrip patch antennas. Characteristics of the patch antenna will be discussed in chapter 4 of this thesis.

2.3.2 Microstrip Traveling-Wave Antennas

![Microstrip Traveling-Wave Antennas](image)

Microstrip traveling-wave antennas consist of chain-shaped periodic conductors or an ordinary long TEM line which also supports a TE mode, on a substrate backed by a ground plane. The open end of the TEM line is terminated in a matched resistive load.
Due to the fact that the antennas support traveling waves, their structures are designed so that the main beam lies in any direction from broadside to endfire. The main aim of this thesis is to understand and analyze such traveling-wave antennas, namely the Linearly Tapered Slot Antenna and the Quasi-Yagi Antenna. Shown in figure 2.6 on the previous page are the various configurations for the microstrip traveling-wave antennas.

2.3.3 Microstrip Slot Antennas

Microstrip slot antennas comprise of a slot in the ground plane fed by a microstrip line. The slot may be shaped like a rectangle, a circle or an annulus as shown in figure 2.7.
Another name used for such antennas is called “Aperture microstrip antenna”. For this thesis, as not much emphasis has been placed on this type of antenna, it will not be discussed in detail.

### 2.4 Excitation Techniques

There are many techniques used to feed or excite microstrip antennas. As most microstrip antennas have radiating elements on one side of a dielectric substrate, it is therefore necessary to be fed by either a microstrip or coaxial line. Matching is normally required between the feed line and the antenna. The reason for this is because the antenna input impedances is different from the normal 50-ohm line impedance. Matching can be achieved by correctly choosing the position of the feed line. On the other hand, the position of the feed may also affect the radiation characteristics. Both the feeding techniques, microstrip and coaxial feeds, will be briefly discussed in the following sections.

#### 2.4.1 Microstrip Feed

Shown in figure 2.8 in the following page are the centre microstrip feed and off-centre microstrip feed antenna arrangements. The position of the feed point will determine which mode is excited. After deciding the size of the antenna element, the matching procedure will be as follows. The center-fed antenna patch is etched together with the 50-ohm feed line. The input impedance is measured and a matching transformer is designed. After reconstructing the antenna, it is then incorporated to the matching section between the antenna element and the feed line. However, if the antenna geometry supports only the dominant mode, the microstrip feed line can be placed towards a corner in order to achieve a good match.
Normally, the antenna mode can be excited in a lot of methods. If the field differs along the width of a rectangular patch antenna and the feed is shifted across the width, the input impedance will change. Although the change in feed position may affect a small shift in resonant frequency (due to change in coupling between feed line and antenna), the radiation pattern will remain unchanged. The shifts in resonant frequency can be compensated by altering the antenna dimensions slightly.
2.4.2 Coaxial Feed

Shown above are the various coaxial feed excitations. The coaxial connector is attached to the backside of the printed circuit board and the coaxial centre conductor is attached to the antenna conductor. The position of the connector is found empirically for the given mode as that which produces the best match. The coaxial feed is also easy to fabricate and match, and it has low spurious radiation. However, it also has narrow bandwidth and is more difficult to model, especially for thick substrates.
CHAPTER 3

LITERATURE REVIEW

This chapter gives a literature review relating to the microstrip design. The chapter starts by providing the design formulas for calculating the effective dielectric constant, followed by the derivations for free-space wavelength and guide wavelength. The characteristic impedance is then defined and analyzed, together with all its related design equations. After giving an explanation of the synthesis equations developed by Wheeler, the microstrip relationship plots for the characteristic impedance and effective dielectric constant versus w/h are then given. Lastly, the chapter ends with an analysis of microstrip discontinuities, providing a list of all the various common discontinuities found in microstrip antenna designs.
3.1 Microstrip Design Formulas

3.1.1 Effective Dielectric Constant

The effective dielectric constant $\varepsilon_{\text{eff}}$ is usually not equal to the dielectric constant $\varepsilon_r$ for a non-uniform structure. For a uniformly filled structure such as a strip line, coaxial line, or parallel plate, the effective dielectric constant is equal to the dielectric constant of the material ($\varepsilon_{\text{eff}} = \varepsilon_r$). However, for microstrip structures, it is necessary to calculate the effective dielectric constant of the structure. Firstly, assume two extreme cases for the effective dielectric constant. Shown below in figure 3.1 are two cases whereby the width of the microstrip $w$ is much greater than the thickness of the substrate ($w \gg h$) in the top diagram and in the bottom diagram, width $w$ is much smaller than the thickness of the substrate ($w \ll h$) [1].

![Figure 3.1: Extremely wide ($w \gg h$) and extremely narrow ($w \ll h$) microstrip lines](image)

Looking at the diagram, for the case of $w \gg h$, most of the fields are confined under the strip and the circuit performs like a parallel plate. Hence, the effective dielectric constant for $w \gg h$ is approximately equal to the dielectric constant. As for the case of $w \ll h$, half of the fields are in the air and the remaining half is in the dielectric substrate (assuming $\varepsilon_r = 1$). As a result, $\varepsilon_{\text{eff}} \approx \frac{1}{2} (\varepsilon_r + 1)$. Therefore, the range of the effective dielectric constant is:

$$\frac{1}{2}(\varepsilon_r + 1) \leq \varepsilon_{\text{eff}} \leq \varepsilon_r$$  \hspace{1cm} (3.1)
Chapter 3: Literature Review

However, equation (3.1) is only a rough estimate of the range of the effective dielectric constant. In order to calculate the exact value of $\varepsilon_{\text{eff}}$, it is necessary to assume a strip thickness $t = 0$. After assuming negligible strip thickness, the derived formulas for the effective dielectric constant is shown below as equations (3.2) and (3.3).

$$
\varepsilon_{\text{re}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \left( 1 + \frac{12}{w/h} \right)^{\frac{1}{2}} + 0.04 \left( 1 - \frac{w}{h} \right)^2 \right] \text{for } \frac{w}{h} \leq 1 \quad (3.2)
$$

$$
\varepsilon_{\text{re}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{12}{w/h} \right)^{\frac{1}{2}} \text{for } \frac{w}{h} \geq 1 \quad (3.3)
$$

### 3.1.2 Wavelength

For any propagating wave, the velocity is given by the appropriate frequency-wavelength product [1]. In free space, $c = f \lambda_0$ and in the microstrip, the velocity is $v_p = f \lambda_{\text{eff}}$. Since the effective dielectric constant $\varepsilon_{\text{eff}}$ is given by

$$
\varepsilon_{\text{eff}} = \left( \frac{c}{v_p} \right)^2 \quad (3.4)
$$

Equating equation (3.4) with the two above-mentioned equations will result in

$$
\varepsilon_{\text{eff}} = \left( \frac{\lambda_0}{\lambda_{\text{eff}}} \right)^2
$$

or

$$
\lambda_{\text{eff}} = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}} \quad (3.5)
$$

where $\lambda_0$ is the free-space wavelength.
3.1.3 Characteristic Impedance

When a generator is suddenly connected to a length of transmission line, there will be a time delay until the signal travels to the other end of the line. During this time, the generator has no knowledge of how long the line might be. The generator has to supply energy to the line so as to establish the electromagnetic fields around the conductors. The energy is stored in the capacitance between the conductors (proportional to the square of the voltage between the wires) and in the magnetic field around the conductors which represents series inductance (proportional to the square of the current on the conductors). Even though the line may be open circuit at the other end, the generator is not aware of it and hence continues to supply current. Therefore, the product of current and voltage is the rate at which energy is supplied to the line. This can be obtained by multiplying the stored electric plus magnetic energy per unit length of line with the velocity at which the signals travel.

The ratio of voltage (between the wires) to current (along one wire and back along the other) has dimensions of impedance or resistance. At a single frequency, on a lossless line, the current is in phase with the voltage and the impedance is real. This impedance is defined as the "Characteristic Impedance". The usual algebraic symbol for the characteristic impedance is \( Z_0 \). The characteristic impedance does not depend on what is connected to the ends of the line, but only on the line geometry and the material construction.

The characteristic impedance, although real and looking like a resistance, is actually a lossless, non-dissipative impedance. In fact, nothing gets hot as a result of supplying energy to this resistance. The reason behind that is because the energy transferred from the generator is stored temporarily in the transmission line. At some later time, possibly a great many transit times later, it can be extracted and returned to the generator, or used to make a real resistive dissipative load become hot.

The characteristic impedance of any line is a function of the geometry of the line and the dielectric constant. For a transmission line, its characteristic impedance is defined as
the ratio of voltage and current of the traveling wave. Hence, the characteristic impedance of a microstrip line of width \( w \) is governed by the following two equations [2]:

\[
Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \left( \ln \left( \frac{8}{w/h} + 0.25 \frac{w}{h} \right) \right) for \frac{w}{h} \leq 1 \quad (3.6)
\]

\[
Z_0 = \frac{120\pi}{\sqrt{\varepsilon_r}} \left( \frac{1}{w/h} + 1.393 + 0.667 \ln \left( \frac{w/h}{1.444} \right) \right) for \frac{w}{h} \geq 1 \quad (3.7)
\]

Note that the equations for \( Z_0 \) and \( \varepsilon_{\text{eff}} \) are only applicable with negligible strip thickness. However, for a finite thickness \( t \), the electric field from the edge makes the line width \( w \) appear to be larger. If \( t/h \geq 0.005 \), then the fringing field effects at the edges of the microstrip should be taken into account. Hence, the actual microstrip widths presented above are replaced by the effective width \( w_{\text{eff}} \):

\[
w_{\text{eff}} = w + \frac{t}{\pi} \left[ 1 + \ln \left( \frac{2}{t/h} \right) \right] for \frac{w}{h} \geq \frac{1}{2\pi} \quad (3.8)
\]

\[
w_{\text{eff}} = w + \frac{t}{\pi} \left[ 1 + \ln \left( \frac{4\pi}{t/w} \right) \right] for \frac{w}{h} \leq \frac{1}{2\pi} \quad (3.9)
\]

### 3.1.4 Synthesis Equations

The width-to-height \((w/h)\) is a strong function of \( Z_0 \) and of the substrate permittivity \( \varepsilon_r \). In addition, the characteristic impedance of a microstrip transmission line is also related to its width. As for the length of the line, it does not have much significance on the impedance characteristics. Hence, various formulas had been derived for microstrip
calculations [2]. Wheeler developed this formula according to the relationship of the line width with its characteristic impedance and substrate permittivity.

\[
\frac{w}{h} = \frac{8 \exp H'}{\exp(2H') - 2}
\]  

(3.10)

where

\[
H' = \frac{Z_0 \sqrt{2(\varepsilon_r + 1)}}{120} + \frac{1}{2} \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right) \left( \ln \frac{\pi}{2} + \frac{1}{\varepsilon_r} \ln \frac{4}{\pi} \right)
\]  

(3.11)

However, if the characteristic impedance \( Z_0 < 44 - 2\varepsilon_r \), the ratio of the width of the microstrip line and the dielectric thickness is given by

\[
\frac{w}{h} = \frac{2}{\pi} \left[ (d_e - 1) - \ln(2d_e - 1) \right] + \frac{\varepsilon_r - 1}{\varepsilon_r} \left[ \ln(d_e - 1) + 0.293 - \frac{0.517}{\varepsilon_r} \right]
\]  

(3.12)

where

\[
d_e = \frac{60\pi^2}{Z_0 \sqrt{\varepsilon_r}}
\]  

(3.13)
3.1.5 Microstrip Relationship Plots

Figure 3.2: Characteristic Impedance versus $w/h$ for microstrip with $\varepsilon_r$ as parameter.

Figure 3.3: Effective Dielectric Constant and Normalized Guide Wavelength of Microstrip versus $w/h$ with $\varepsilon_r$ as parameter.
Figure 3.4: Comparison of Impedance Characteristics of Microstrip, Suspended Microstrip and Inverted Microstrip. $\varepsilon_r = 3.78$.

From the above plot in figure 3.4, it can be seen that higher characteristics impedance can be achieved by using either suspended or inverted types of microstrip [2].

### 3.2 Microstrip Discontinuities

All practical distributed circuits, either in waveguide, coaxial lines or any other propagation structure, must naturally contain discontinuities [1]. A straight, uninterrupted length of waveguide or microstrip would be considered continuous but would also be of little of engineering use. Hence, discontinuities in microstrip lines are commonly an integral part of microstrip antennas, occurring both in the feeder lines and radiating elements. Radiating elements can be regarded as desirable discontinuities in the sense that the radiation loss created can be usefully employed in the antenna design. However, discontinuities in feeder lines create unwanted radiation which can corrupt the radiation pattern of the antenna. As a matter of fact, in actual circuits, transmission lines are neither straight nor infinite. The lines would start and stop at some definite
points, bend, change width, branch out, etc. Shown below in figure 3.5 are the various types of microstrip discontinuities.

![Figure 3.5: Various Types of Microstrip Discontinuities](image)

It is very important to characterize accurately the discontinuities in microstrip circuits [14]. The reason for this is because it is not easy to adjust or modify microstrip circuits after the fabrication of the circuit is completed. If a provision is made for adjustments, the main advantages of compactness and reliability gained by the use of microstrip circuits are lost.

A discontinuity in microstrip is caused by abrupt change in the geometry of the strip conductor. Hence, the electric and magnetic field distributions near the discontinuity are then modified. The modified electric field distribution would then give rise to a change in capacitance whereas the changed magnetic field distribution can be written in terms
of an equivalent inductance. Therefore, the analysis of microstrip discontinuity would involve the evaluation of these capacitances and inductances.

Microstrip discontinuities are difficult to analyze, due to their inhomogeneous nature and the presence of radiation together with propagation phenomena [15]. However, analysis of microstrip discontinuities can either be based on quasi-static considerations or by full wave analysis. Quasi-static analysis involves calculations of static capacitances and low frequency inductances. As for full wave analysis, it is much more complicated and will not be discussed in this thesis.
CHAPTER 4

MICROSTRIP BROADBAND PLANAR ANTENNAS

This chapter gives a background information with regard to microstrip broadband planar antennas. The three most commonly used broadband planar antennas are presented, namely the Microstrip Patch antenna, Quasi-Yagi antenna and Tapered Slot Antenna. Advantages and disadvantages of these antenna structures will also be included. In addition, analysis and synthesis of such antennas are also discussed in detail. Lastly, the chapter ends by giving a brief explanation on spatial power combining, including four possible power-combining architectures.
4.1 Microstrip Patch Antennas

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Directivity</th>
<th>Polarization</th>
<th>Bandwidth</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patch</td>
<td>Broadside</td>
<td>Medium</td>
<td>Linear/Circular</td>
<td>Narrow</td>
</tr>
<tr>
<td>Slot</td>
<td>Broadside</td>
<td>Low/Medium</td>
<td>Linear</td>
<td>Medium</td>
</tr>
<tr>
<td>Ring</td>
<td>Broadside</td>
<td>Medium</td>
<td>Linear/Circular</td>
<td>Narrow</td>
</tr>
<tr>
<td>Spiral</td>
<td>Broadside</td>
<td>Medium</td>
<td>Linear/Circular</td>
<td>Wide</td>
</tr>
<tr>
<td>Bow-Tie</td>
<td>Broadside</td>
<td>Medium</td>
<td>Linear</td>
<td>Wide</td>
</tr>
<tr>
<td>TSA(Vivaldi)</td>
<td>Endfire</td>
<td>Medium/High</td>
<td>Linear</td>
<td>Wide</td>
</tr>
<tr>
<td>LPDA</td>
<td>Endfire</td>
<td>Medium</td>
<td>Linear</td>
<td>Wide</td>
</tr>
<tr>
<td>Leaky-Wave</td>
<td>Scannable</td>
<td>High</td>
<td>Linear</td>
<td>Medium</td>
</tr>
<tr>
<td>Quasi Yagi</td>
<td>Endfire</td>
<td>Medium/High</td>
<td>Linear</td>
<td>Wide</td>
</tr>
</tbody>
</table>

Figure 4.1: Planar Antenna Selection Chart

Microstrip broadband planar antennas have been of interest to antenna designers for many years in microwave and millimeter-wave integrated systems. A planar configuration implies that the characteristics of the element can be determined by the dimensions in a single plane. Despite their planar geometry, the antennas can produce a symmetric beam, often over a wide band of frequencies. Shown above in figure 4.1 is the planar antenna selection chart. From the chart, it can be seen that while both the Tapered Slot antenna and the Quasi-Yagi antenna possess wide bandwidth and end-fire radiation pattern, the microstrip patch antenna has narrow bandwidth and produces broadside radiation.

4.1.1 Conventional Microstrip Patch Antenna

A conventional microstrip patch antenna is often referred to as a printed patch antenna. It consists of a printed conducting patch (normally of rectangular or circular shape) which is placed on the upper surface of a dielectric substrate. A conducting ground plane can be found at the back of the dielectric substrate. It is a parallel resonant circuit. The
ground plane is the place where an electromagnetic field is initially developed. The radiation from the field is present not only in the substrate but also in the air. This radiation pattern is defined as broadside direction and can be seen in figure 4.2 below:

![figure 4.2](image)

**Figure 4.2: Broadside Radiation Direction of Microstrip Patch Antenna**

The bandwidth of a microstrip patch antenna is also referred as the input impedance bandwidth and is usually defined as a frequency range over which the return loss of the antenna is below 10dB. The feeding structure of the antenna plays an important role in its input impedance bandwidth.

### 4.1.2 Aperture Coupled Microstrip Patch Antenna

Rectangular and circular patch antennas provide linear polarization. By using the square or circular patch antennas, circularly polarized radiation can be synthesized when fed appropriately at two ports. A microstrip patch antenna can be fed directly by a microstrip line either on the same plane or through a slot in a ground plane (which is also known as the aperture). Such an antenna is called the aperture coupled microstrip patch antenna as shown in figure 4.3. By using slant-slot in aperture coupled patch antenna, circularly polarized radiation can also be excited. The advantages of using such
an antenna are that they are thin and can be easily fabricated. Excitation of these antennas is also easy. In addition, there is also a reduction of spurious radiation from the microstrip feed line. Spurious radiation is not desirable as it corrupts the side lobes or polarization of the antenna. On the other hand, the disadvantage of these antennas is that they are extremely narrow-band, of the order of 1-5%. For high dielectric substrate, the resonant frequency is very sensitive to dimensional deviation.

![Figure 4.3: Microstrip Aperture Coupled Patch Antenna](image)

**4.1.3 Microstrip Patch Antenna Array**

Microstrip patch antennas are also often used in arrays because of its low gain and wide beamwidth. An example of an array made up of microstrip patch antennas is shown in figure 4.4. Due to the fact that the array consists of many patch antennas, the feeding structure of the array is definitely more complicated than that of a single element. In addition, coupling will also occur between the microstrip single elements, the feeding structure and the substrates in the array. As a result, when considering the bandwidth of the array, it is necessary to consider the effects of coupling.
Microstrip patch antennas have found applications in a number of areas of wireless communications. The reason for this is because of its inherent features such as planar appearance, low weight and low development costs. In addition, microstrip patch antennas can also be easily be integrated with oscillators and amplifiers. Moreover, although microstrip patch antennas are narrowband, it will be able to achieve broadband characteristic either by employing multilayer structures with aperture coupling or by introducing parasitic slots inside the patch. On the other hand, aperture coupling is difficult to fabricate and it also has narrow bandwidth. The other drawbacks are that this type of antenna is associated with their small dimensions at higher operation frequency. Hence, manufacturing difficulties will occur when these antennas are used at millimeter wave frequencies.
4.2 Microstrip Quasi-Yagi Antennas

Another type of microstrip broadband antenna is the uniplanar Quasi-Yagi antenna. This antenna utilizes a similar principle as a conventional Yagi-Uda dipole array where the electromagnetic energy is coupled from the driven element dipole through space into the parasitic dipoles and then reradiated to form a directional beam. However, unlike the traditional Yagi-Uda dipole design, a truncated microstrip ground plane is used in the Quasi-Yagi antenna as the reflecting element, thus eliminating the need for a reflector dipole.

4.2.1 Uniplanar Quasi-Yagi Antenna

The Quasi-Yagi antenna shown in figure 4.5 consists two dipole antennas, the director and the driver, a truncated ground plane and a microstrip-to-coplanar strips (CPS) balun [16]. The director and driver of the antenna are placed on the same plane of the high dielectric substrate so that the surface waves generated by the antenna is directed to the end-fire direction. Coplanar strips is a uniplanar transmission line and a balun is usually desired to provide efficient transition between the CPS and the microstrip lines [17]. The truncated ground plane is on the bottom side of the substrate. This antenna design is unique in the sense that the truncated ground plane on the back of the substrate acts as a reflecting element [18]. In other words, the ground plane helps to reduce the surface wave traveling to the backside. The dipole elements of the antenna are strongly coupled by the surface waves which has the same polarization and direction as the dipole radiation fields [19]. As for the radiation direction of the Quasi-Yagi Antenna, it belongs to the general class of end-fire traveling-wave antennas. Shown in figure 4.6 is the end-fire radiation characteristic of the Quasi-Yagi antenna.
Figure 4.5: Uniplanar Quasi-Yagi Antenna

Figure 4.6: End-Fire Radiation Direction of Quasi-Yagi Antenna
4.2.2 Advantages and Disadvantages of Quasi-Yagi Antenna

The unique design of the Quasi-Yagi antenna results in an antenna with relatively high directivity, high gain and wide bandwidth. In fact, the Quasi-Yagi antenna possesses both the compactness of resonant-type antennas and also the broadband characteristics of traveling-wave radiators. The simple and very compact structure is also totally compatible with any microstrip-based MMIC circuitry. The antenna is easy to fabricate due to its uniplanar nature. Similar to the LTSA, the Quasi-Yagi antenna also possesses end-fire radiation patterns. The difference is that the Quasi-Yagi antenna is more compact than a Vivaldi or tapered slot antenna. In addition, it is fed by a standard microstrip line, thus making the monolithic integration of the antenna and detectors easy. Moreover, the antenna provides a suitable bandwidth to match with individual transistor amplifiers. In addition, the antenna also shows better cross-polarisation and front-to-back ratio at the centre of the operating band of the antenna. Therefore, this antenna should find wide applications in spatial power combining and other wireless communications systems.
4.3 Microstrip Tapered-Slot Antennas

For very wideband operation, large-traveling wave or self-complementary antennas must be used. An attractive choice for arrays is the end-fire tapered slot structure. Microstrip tapered slot antenna is also an antenna with wideband characteristics. It has a larger operational bandwidth and a higher gain compared to the microstrip patch antenna.

4.3.1 Types of Tapered Slot Antenna

A typical tapered slot antenna (TSA) consists of a tapered slot cut in a thin film of metal with or without an electrically thin substrate on one side of the film. As the slot moves towards another end of the substrate, it becomes narrower. The purpose of the narrow slot is for efficient coupling to devices such as mixer diodes. The slot is tapered at the end of the substrate and a traveling wave propagating along the slot radiates in the end-fire direction. Shown below in figure 4.7 are three TSA elements with different shapes of the taper [20].

![Figure 4.7: Different Types of End-Fire Tapered Slot Antenna](image)

All these three antennas belong to the family of end-fire traveling wave antennas. The first tapered slot antenna on the left is the Vivaldi antenna. This antenna, developed by Gibson in 1979, consists of a metalized dielectric substrate with an exponentially tapered slot in the metalization, with the width increasing progressively at the end. The remarkable feature of the Vivaldi antenna is that it radiates at the end-fire
direction with much higher gain and wider bandwidth compared to microstrip patch antennas.

The second and third antennas in the diagram are the linearly tapered slot antenna (LTSA) and the constant width slot antenna (CWSA). All these three antennas produce a symmetric endfire beam, meaning that they radiate along the long direction of the substrate. The radiated electric field is linearly polarized and is parallel to the plane of the slot. The end-fire radiation pattern of tapered slot antennas is shown in figure 4.8 below.

![End-Fire Radiation Pattern of Tapered Slot Antenna](image)

Figure 4.8: End-Fire Radiation Pattern of Tapered Slot Antenna

The LTSA has lots of outstanding features like narrow beam width, high element gain, wide bandwidth and small transverse spacing between elements in an array. In addition, due to its end-fire radiation characteristic, it is suitable for inclusion as an element of a brick array. However, the disadvantage of LTSA is that it has a relatively large antenna size. Moreover, it also requires a microstrip-to-slot or coplanar waveguide (CPW)-to-slot transition as part of its feeding network. As a result, the antenna design complexity increases and there’s also a limit on the broad frequency bandwidth.
4.3.2 Definition of E- and H-plane for TSAs

Shown in Figure 4.9 is the definition of the electric and magnetic radiating fields of a tapered slot antenna. Due to its end-fire radiation characteristics, the E-plane is defined to be on the same plane as to where the tapered slot antenna is located. As for its H plane, it is found to be in perpendicular to the E-plane. Hence, it can be seen that the planes’ definition for TSAs is different from the microstrip patch antenna as its E and H-plane are both perpendicular to the plane where the patched is positioned. Hence, it is the beauty of tapered slot antennas that they can produce a symmetric beam (in E- and H-planes), often over a wide band of frequencies, despite their planar geometry.

![Figure 4.9: Definition of E- and H-planes for TSAs](image)

4.3.3 Advantages and Disadvantages of Tapered Slot Antenna

The input impedance of tapered slot antennas is essentially that of the feed transmission line as the antenna structure is a broadband impedance transformer. These antennas are highly compatible with traveling-wave or distributed circuits, such as nonlinear transmission lines and traveling-wave amplifiers. At millimeter wavelengths, both these technologies would benefit from the increased power-handling capability afforded by quasi-optical arrays. In turn, the quasi-optical array concept will benefit from the large
bandwidth and reduced sensitivity to device or processing variations afforded by distributed circuits.

Although tapered slot antennas usually have a larger electrical size than resonant-type patches or slots, its drawback is usually its small operational bandwidth due to its resonant nature. However, broader bandwidth and higher directivity can be achieved compared to the other structures. Another problem is its small dimensions at higher operation frequency as manufacturing difficulties would surfaced, especially when these antennas are to be used at millimeter frequencies. In addition, tapered slot antennas also require microstrip-to-slot or CPW-to-slot transitions as part of its feeding network. This limitation would not only increase the antenna’s design complexity but also imposes a limit on the frequency response. Nevertheless, tapered slot antennas have found important applications in radio astronomy, remote sensing, multiple beam satellite communications and spatial power combining.

4.4 Spatial Power Combining

Spatial power combining was reported as early as 1968 and quasi-optical approaches have dominated the research on spatial power combining only recently [21]. However, more traditional antenna and microwave techniques are gaining interest in designs for spatial power combining systems. In order to increase the output power of solid-state amplifiers at millimeter wave frequencies, the output power from many devices must be combined. Due to the fact that conventional power combining techniques are inefficient at millimetre frequencies, spatial or quasi-optical power amplification had to be performed. The advantages of quasi-optical power combiners over conventional power combiners are higher combining efficiency and larger dimensional tolerances. A typical quasi-optical system consists of passive components (horns, polarizers, lenses, etc) and active components (antenna arrays, patch arrays, etc).
Shown above are four possible power-combining architectures. The circuit-fed/circuit-combined approach on the top left corner is the conventional approach for solid-state amplifiers. As for the circuit-fed/spatially combined design on the top right corner, it is the configuration used for typical antenna arrays. The spatially-fed/circuit-combined approach on the bottom left corner is normally not used. Lastly, the spatially-fed/spatially-combined array on the bottom right corner is the most common type of spatial power-combining array. Basically, the concept of spatially-fed/spatially-combined approach is shown in figure 4.11 in the following page.
Figure 4.11 from [22] shows two LTSAs integrated with a MMIC three-stage power amplifier in each of the antenna elements. Low power signals launched from the horn antenna on the right are received by the array of LTSA in the middle, amplified by the MMIC amplifiers and re-radiates into free space through another array of LTSA. The amplified signal is then received by the other horn antenna on the left.
CHAPTER 5

DESIGN AND DEVELOPMENT OF MICROSTRIP BROADBAND PLANAR ANTENNAS

This chapter covers the entire design and development of two kinds microstrip broadband planar antennas, namely the Quasi-Yagi antenna and the Linearly Tapered Slot antenna. The steps involved in obtaining the dimensions for both the antennas are shown in detail. The designs for the two antennas are aimed at obtaining wider bandwidth and better radiation patterns. In addition, the design considerations like the geometry parameters and the materials selected for the antenna are also presented.
5.1 Design of Uniplanar Quasi-Yagi Antenna

Most of the previous research done on broadband antennas has always been focusing on designing an antenna with low dielectric constant substrate materials. Not much research had been done on building antennas using a high dielectric constant substrate. The reason for using low dielectric constant material is that better radiation efficiency and larger bandwidth can be obtained. However, for this thesis, a high dielectric constant material, Duroid ($\varepsilon_r = 10.2$) substrate, would be used in the design of both the LTSA and the Quasi-Yagi antenna. The substrate used is 0.635 mm thick and the design frequency will be at 12.5 GHz.

5.1.1 Design Considerations

Realizing the required design considerations is a fundamental procedure before the design of any antennas. Hence, before calculating the dimensions of both the antennas, it is very important to obtain the free-space wavelength $\lambda_o$ and the guide wavelength $\lambda_G$ required by the antennas. Both these parameters are vital in the designs of the Quasi-Yagi antenna and the LTSA. In order to acquire these parameters, it is necessary to refer to section 3.1.2 of chapter 3 in this thesis. Equation 3.5 showed how the guide wavelength $\lambda_G$ could be obtained. However, the value of the effective dielectric constant $\varepsilon_{ef}$ is needed in order to obtain the value of the guide wavelength. From chapter 3 section 3.1.1, the formulas for calculating effective dielectric constant is shown. It can be seen from the section that there are two sets of equation for calculating the effective dielectric constant. Due to the fact that the width-to-thickness $w/h$ ratio for the design is smaller than 1, equation 3.2 will be used to calculate the effective dielectric constant. On the other hand, the effective dielectric constant can also be obtained using the software PCAAD. From PCAAD, the simulated effective dielectric constant obtained is 6.947. Using the effective dielectric constant $\varepsilon_{ef}$, design frequency of 12.5 GHz, speed
of light \( c \), the calculations for the free-space wavelength, effective dielectric constant and guide wavelength is shown below.

Free-space wavelength \((\lambda_o) = c / f\)

\[
= 3 \times 10^8 / 12.5 \times 10^9
= 24 \text{ mm}
\]

Effective dielectric constant =

\[
\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ \left( 1 + \frac{12}{w/h} \right)^{\frac{1}{2}} + 0.04 \left( 1 - \frac{w}{h} \right)^2 \right] = 6.8433
\]

Guide wavelength \((\lambda_G) = \lambda_o / \varepsilon_{eff}\)

\[
= 24 \times 10^{-3} / 6.8433
= 9.17 \text{ mm}
\]

Note that the simulated value of the effective dielectric constant (6.947) is very close to the calculated value (6.8433). Hence, for accuracy purposes, the calculated effective dielectric constant is used for the design.

5.1.2 Antenna Dimensions

Once the free-space wavelength and the guide wavelength have been obtained, the dimensions of the Quasi-Yagi antenna could be calculated. The schematic diagram of the Quasi-Yagi antenna is shown as figure 5.1 in the next page.
Chapter 5: Design and Development of Microstrip Broadband Planar Antennas

Figure 5.1: Schematic diagram of Quasi-Yagi Antenna

Looking at the schematic diagram of the Quasi-Yagi antenna, it can be seen that there are a lot of dimensions that need to be determined. The width $W_1$ is supposed to be connected to the microstrip feed and to the power amplifier for spatial power combining. The value of $W_1$ has to be designed so that the characteristic impedance of the conventional microstrip ($50\,\Omega$) to the balanced microstrip could be matched. There are a number of ways to determine the width of the microstrip, but the way which was done for this design is using the synthesis formulae. The synthesis equations derived by Wheeler can be found in section 3.1.4 of chapter 3 in this thesis. Before using this method, the characteristic impedance $Z_0$ and the dielectric constant $\varepsilon_r$ have to be given.
In addition, this method is only applicable to narrow microstrip lines. The calculations for the microstrip width-to-substrate thickness ratio \( \frac{w}{h} \) is shown below:

\[
\frac{w}{h} = \frac{8 \exp H'}{\exp (2H') - 2} = \frac{8 \exp(2.16722)}{\exp(2 \times 2.16722) - 2} = 0.94063
\]

where

\[
H' = \frac{\sqrt{2(\varepsilon_r + 1)}}{120} + \frac{1}{2} \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right) \left( \ln \frac{\pi}{2} + \frac{1}{\varepsilon_r} \ln \frac{4}{\pi} \right)
\]

\[
= \frac{50 \sqrt{2(10.2 + 1)}}{120} + \frac{1}{2} \left( \frac{10.2 - 1}{10.2 + 1} \right) \left( \ln \frac{\pi}{2} + \frac{1}{10.2} \ln \frac{4}{\pi} \right)
\]

\[
= 2.16722
\]

After inserting the value of \( Z_0 = 50 \Omega \) and dielectric constant \( \varepsilon_r = 10.2 \), the microstrip line width-to-substrate thickness ratio \( \frac{w}{h} \) is obtained. In order to find out the microstrip width required to match a \( 50 \Omega \) line, it is necessary to multiply the \( \frac{w}{h} \) ratio with the substrate thickness of 0.635mm. The resulting width obtained would be approximately 0.6mm. Alternatively, the microstrip width can also be found by using the software PCAAD. This software allows the user to obtain the microstrip width value easily by just entering the required values for the antenna design. The result obtained from PCCAD is similar to the calculated results shown above. After obtaining the value of \( W_1 \), it can be seen from the diagram that the value of \( W_1 \) is similar to \( W_3, W_4, W_6, W_{di} \) and \( W_{dir} \). Hence, all these six dimensions are set to be 0.6 mm. As for the values of \( W_2 \) and \( W_s \), they are chosen to be 1.2 mm and 0.3 mm respectively.

\[
Z_0 = \frac{60}{\sqrt{\varepsilon_r \varepsilon}} \ln \left( \frac{8}{w/h} + 0.25 \frac{w}{h} \right) = \frac{60}{\sqrt{6.8433}} \ln \left( \frac{8}{0.94063} + 0.25(0.94063) \right) = 50 \Omega
\]

On the other hand, the characteristic impedance can also be verified by using the equation 3.6 found in section 3.1.3 of chapter 3. The resulting characteristic impedance obtained is shown to be 50 ohms, which proved that the \( \frac{w}{h} \) ratio used is effective in
matching characteristic impedance of the conventional microstrip (50Ω) to the balanced microstrip.

Next, the length of the driver and director of the antenna is to be determined. From [23], parameter study of a broadband uniplanar Quasi-Yagi antenna, it is found that the most sensitive parameters are the length of the driver \(L_{\text{dri}}\) and the distance from the driver to the reflector \(S_{\text{ref}}\). The antenna’s design frequency and its operational bandwidth will be affected by these two parameters. Thus, the paper stated that the length of the driver would be optimum when it is about a guide wavelength and the distance between the driver and the reflector is about a quarter guide wavelength. Therefore, the calculations are done and shown below.

\[
L_{\text{dri}} = \frac{\lambda}{4} \approx 9.17 \text{ mm}
\]

\[
S_{\text{ref}} = \frac{\lambda}{4} = 2.2925 \text{ mm}
\]

In addition, the paper also states that a change in the length of the director \(L_{\text{dir}}\) and the distance between the director and the driver \(S_{\text{dir}}\) does not affect the design frequency and operational bandwidth. Moreover, the length of the gap between the coupled microstrip lines \(S_6\) only affects the bandwidth moderately. Thus, the value of \(L_{\text{dir}}\) is set to be 4.8 mm, \(S_{\text{dir}} = 2.5 \text{ mm}\) and \(S_6 = 0.5 \text{ mm}\). However, further analysis on the effects of the length of the driver \(L_{\text{dri}}\) and the distance from the driver to the reflector will be investigated in the next chapter, where five parameters of the Quasi-Yagi antenna will be analyze with respect to the \(S_{11}\) return loss.

In [17] and [24], it is stated that by designing impedance matched T-junction and delaying one side of the microstrip line by half wavelength at the desired frequency \((L_3 - L_2 = \frac{\lambda}{4})\), it will result in a predominantly odd mode in the coupled microstrips. This means that the propagation mode in the coupled microstrips will be dominantly the odd mode, which can be easily transferred into the coplanar CPS mode after the ground plane is truncated. Thus, the value of \(L_3 = 5.08 \text{ mm}\) and \(L_2 = 2.79 \text{ mm}\) so that when \(L_3 - L_2\) is equal to 2.29mm.
Figure 5.2: Actual Size of Quasi-Yagi Antenna

Shown above in figure 5.2 is the actual size of the Quasi-Yagi antenna after fabrication. Note the compactness of the antenna when it is compared with the size of a coin. After determining the antenna’s dimensions, the full-wave (MoM) method of moment analysis package IE3D of Zeland Software Inc. is used to analyze the performance of the Quasi-Yagi antenna.

5.2 Design of Linearly Tapered Slot Antenna

This section will discuss about the design of another type of microstrip broadband antenna, the Linearly Tapered Slot antenna.

5.2.1 Design Considerations

Similar to the Quasi-Yagi antenna, it is also very important to obtain the free-space wavelength $\lambda_o$ and the guide wavelength $\lambda_G$ required by the LTSA. Hence, due to the fact that the LTSA has to be designed at a frequency of 12.5 GHz and the substrate used has dielectric constant of 10.2 and substrate thickness of 0.635 mm, the free-space wavelength $\lambda_o$, guide wavelength $\lambda_G$ and the effective dielectric constant $\varepsilon_{rt}$ would be the same as the values used for the Quasi-Yagi antenna.
In addition, it is also necessary to consider how the two fins on each side of the substrate overlap each other. For the LTSA, there are two exponentially tapered fins printed on opposite sides of the substrate so as to form a slot over the substrate. As can be seen in figure 5.3 above, the overlap between the two fins (close to the feed point) produces a transmission line that is quasi-TEM in behaviour [25]. As this transmission line is similar to a microstrip line, the characteristic impedance analysis for microstrip line can be applied here. As for the middle section of the LTSA, it also behaves in quasi-TEM mode and its characteristic impedance should be twice the characteristic impedance of the equivalent microstrip line of width $w$ and height $h/2$. As for the last section with reducing width of the overlap, it forms the quasi-TEM impedance taper, followed by a quasi-TE impedance taper. The purpose of the quasi-TE taper is to achieve large characteristic impedance so that it is able to match free-space impedance.

### 5.2.2 Antenna Dimensions

Next, the dimensions for the linearly tapered slot antenna (LTSA) are to be determined. The design for the LTSA followed closely the guidelines stated on [26]. The top metalization and the bottom metalization of the LTSA are shown in figure 5.4.
Figure 5.4: Top and bottom metalization of LTSA

The LTSA shown consists of a conventional microstrip on a dielectric substrate of thickness 0.635 mm. The dielectric constant material used for this design is similar to that used for the Quasi-Yagi antenna mentioned earlier, Duroid (\(\varepsilon_r = 10.2\)). The design frequency is also set at 12.5 GHz. The characteristic impedance of the conventional microstrip is 50\(\Omega\), whereas the input impedance of the LTSA is approximately 160\(\Omega\) (similar to the characteristic impedance of the balanced microstrip). As the input impedance of the LTSA is twice the input impedance of a regular half LTSA above ground plane (80\(\Omega\)), the strip width \(W\) can be calculated using the same synthesis formula as the Quasi-Yagi antenna. The synthesis equations can be found in section 3.1.4 of chapter 3.

\[
\frac{w}{h} = \frac{8 \exp H'}{\exp(2H') - 2} = \frac{8 \exp(3.3504)}{\exp(2 \times 3.3504) - 2} = 0.2812
\]
where

\[ H' = \frac{Z_0}{120} \sqrt{2(\varepsilon_r + 1)} + \frac{1}{2} \left( \frac{\varepsilon_r - 1}{\varepsilon_r + 1} \right) \left( \ln \frac{\pi}{2} + \frac{1}{\varepsilon_r} \ln \frac{4}{\pi} \right) \]

\[ = \frac{80\sqrt{2(10.2+1)}}{120} + \frac{1}{2} \left( \frac{10.2 - 1}{10.2 + 1} \right) \left( \ln \frac{\pi}{2} + \frac{1}{10.2} \ln \frac{4}{\pi} \right) \]

\[ = 3.3504 \]

By multiplying the obtained w/h ratio with the substrate thickness of 0.635mm, the resulting width would therefore be approximately 0.18mm. The value of the arc \( R_2 \) is supposed to be half free space wavelength \( \lambda_0/2 \), which is equal to 12 mm. As for the value of the second arc \( R_1 \), it is chosen arbitrarily as 0.9\( \lambda_0 \), which is equal to 21.6 mm.

As for the flare angle \( \alpha \), it can be seen from the diagram that it is formed by gradually flaring the strip conductors of the balanced microstrip on opposite sides of the dielectric substrate. As stated on [4], maximum aperture efficiency would be achieved if 2\( \alpha \) is close to 11 degrees. Hence, for this design, \( \alpha \) is chosen as 5.3 degrees. The last parameters to consider are the antenna length \( L \) and width \( H \). The width \( H \) had to be greater than \( \lambda_0/2 \) so that the LTSA can operate as a travelling wave antenna. Thus, \( H \) is chosen as 0.75\( \lambda_0 \), which is equal to 18 mm. Last but not least, the length \( L \) of the antenna has to be determined by \( \alpha \) and \( H \), using the equation shown below.

\[ L \tan \alpha = H/2 \]

Thus, after substituting in the values, the obtained value for length \( L \) is 97 mm. This value satisfy the theoretical length value of the LTSA being in the order of 2\( \lambda_0 \leq L \leq 12\lambda_0 \). With the dimensions for the LTSA determined, the next procedure is to analyze the antenna performance.
CHAPTER 6

RESULTS AND DISCUSSION

This chapter provides all the simulated results related to the Quasi-Yagi antenna. The chapter starts by giving a sensitivity analysis of the Quasi-Yagi antenna with respect to five design parameters: the length of the director, distance between the director and the driver, distance between the coupled microstrip lines, length of the driver and distance from the driver to the reflector. The effects of the five parameters on its operational frequency and impedance bandwidth are investigated and the parameters most affecting the performance of the antenna are also identified. In addition, the radiation patterns and parameters generated by the antenna are also shown.
6.1 Sensitivity Analysis of Quasi-Yagi Antenna

From chapter 5, the design guidelines for the Quasi-Yagi antenna have been presented, including all the calculations required for the antenna’s dimension. However, it is necessary to understand how the operational frequency and impedance bandwidth of the antenna is affected by the variation of some parameters’ dimensions. From [23], it shows the parameter study of a broadband uniplanar Quasi-Yagi antenna fabricated on a substrate with relative dielectric constant of 2.45 and substrate thickness of 0.48mm. However, for this thesis, a parameter study of the sensitivity of the Quasi-Yagi antenna with relative dielectric constant of 10.2 and substrate thickness of 0.635mm has been performed at a design frequency of 12.5GHz. Shown below in figure 6.1 is the configuration of the Quasi-Yagi antenna, including the five investigated parameters.

![Figure 6.1: Investigated Parameters of the Quasi-Yagi antenna](image)
6.1.1 Length of Director

The first parameter to investigate is the length of the director of the Quasi-Yagi antenna. From figure 6.1, it can be seen that the length of the director is identified as parameter 1. From [23], it stated that a change in the length of the director $L_{dir}$ does not affect the design frequency and operational bandwidth. Hence, the length of the director is set to be 4.8mm initially. Shown below are the results achieved when the length of the director is varied from 3.8mm to 5.8mm with an increment of 1mm. The results of simulations are presented in terms of $S_{11}$ return loss.

$L_{dir} = 4.8 \text{ mm}$

$L_{dir} = 5.8 \text{ mm}$
From the above simulation results, it can be observed that the return loss degrades when the length of the director is increased. When the length of the director is set at 5.8mm, both the design frequency and the return loss are affected greatly. However, when the length of the director is set at 3.8mm, the simulated results showed an acceptable return loss of –17.5dB at the desired design frequency of 12.5GHz. Hence, it can be deduced that the return loss of the antenna is sensitive to variations of this parameter, as it affects the impedance bandwidth as well as the design frequency.

### 6.1.2 Distance Between Director and Driver

The next parameter to investigate is the distance between the director and the driver, which is labeled as parameter 2 in figure 6.1. From [23], it showed that the distance between the director and driver $S_{\text{dir}}$ has very little effects on the return loss. Therefore, $S_{\text{dir}}$ is set to be 2.5mm initially. The distance is then varied from 1.5mm to 2.5mm with an increment of 0.5mm. The results of simulations in terms of $S_{11}$ return loss are presented in the three plots in the following page.
Chapter 6: Results and Discussion

$S_{\text{dir}} = 2.5 \text{ mm}$

$S_{\text{dir}} = 2 \text{ mm}$

$S_{\text{dir}} = 1.5 \text{ mm}$
From the obtained results, it showed that although all three plots produce a reasonable $S_{11}$ return loss, the best result achieved would be when $S_{\text{dir}}$ is set to be 2mm. At $S_{\text{dir}} = 2$mm, the antenna achieved a good return loss of $-17.5$dB at the desired frequency of 12.5GHz. Therefore, it can be deduced that the impedance bandwidth and the design frequency will also be slightly affected with variations of the distance between the director and driver of the antenna.

### 6.1.3 Distance Between Coupled Microstrip Lines

The distance between the coupled microstrip lines is labeled as parameter 3 in figure 6.1. From [23], the results showed that the return loss becomes worse when the gap between the two microstrip lines $S_6$ is reduced. Hence, $S_6$ is set to be 0.5mm initially. The distance is then varied from 0.3mm to 0.7mm with an increment of 0.2mm. The results of simulations in terms of $S_{11}$ return loss are presented in the three plots below.

![Graph showing $S_{11}$ return loss vs Frequency](image)

$S_6 = 0.5$ mm
Chapter 6: Results and Discussion

After analyzing the three obtained plots, it can be assumed that the return loss would degrades with increasing distance between the coupled microstrip lines. When $S_6$ is set at 0.7mm, the return loss achieved is only $-9$dB at 11GHz. However, when $S_6$ is set at 0.3mm, the antenna obtained a very good return loss of $-21$dB at 10.5GHz. Although the centre frequency is not achieved at the desired frequency of 12.5GHz, variations to other parameters should be able to solve this problem. Therefore, it can be deduced that the return loss would be most desirable when the distance between the coupled microstrip lines is set at 0.3mm.

$S_6 = 0.3$ mm

$S_6 = 0.7$ mm

After analyzing the three obtained plots, it can be assumed that the return loss would degrades with increasing distance between the coupled microstrip lines. When $S_6$ is set at 0.7mm, the return loss achieved is only $-9$dB at 11GHz. However, when $S_6$ is set at 0.3mm, the antenna obtained a very good return loss of $-21$dB at 10.5GHz. Although the centre frequency is not achieved at the desired frequency of 12.5GHz, variations to other parameters should be able to solve this problem. Therefore, it can be deduced that the return loss would be most desirable when the distance between the coupled microstrip lines is set at 0.3mm.
6.1.4 Length of Driver

The next parameter to investigate is the length of the driver which is labeled as parameter 4 in figure 6.1. From [23], it stated that the length of the driver $L_{dri}$ is optimum when it is about a guide wavelength. Therefore, from chapter 5, the value of $L_{dri}$ is calculated to be 9.17 mm, which is equal to the guide wavelength of the antenna. The length of the driver is then varied from 8.17 mm to 10.17 mm with an increment of 1 mm. The results of simulations in terms of $S_{11}$ return loss are presented in the three plots below.

\[ L_{dri} = 9.17 \text{ mm} \]

\[ L_{dri} = 10.17 \text{ mm} \]
From the three graphs shown above, it can be observed that all the plots are able to achieve a centre frequency of 12.5GHz, which is the desired frequency for the design. In addition, in terms of return loss, all three plots also provide reasonable values of return losses. However, when $L_{\text{dri}}$ is set to 8.17mm, the antenna is able to achieve an extremely good return loss of $-27\text{dB}$ and a very wide bandwidth. Hence, it can be deduced that in order to achieve good return loss and wide bandwidth, it is necessary for the length of the driver to be less than the guide wavelength, most preferably about 1mm less than $\lambda_G$.

### 6.1.5 Distance From the Driver to the Reflector

The last parameter to investigate is the distance from the driver to the reflector, labeled as parameter 5 in figure 6.1. From [23], it showed that the best result could be obtain if the distance from the driver to the reflector $S_{\text{ref}}$ is about a quarter guide wavelength. Thus, as shown in chapter 5, the value of $S_{\text{ref}}$ is calculated to be 2.29mm, which is equivalent to a quarter guide wavelength. The distance is then varied from 1.29mm to 3.29mm with an increment of 1mm. The results of simulations in terms of $S_{11}$ return loss are presented in the three plots in the following page.
Chapter 6: Results and Discussion

$S_{\text{ref}} = 2.29 \text{ mm}$

$S_{\text{ref}} = 1.29 \text{ mm}$

$S_{\text{ref}} = 3.29 \text{ mm}$
After analyzing the results, it can be observed that the deductions from [23] can also be applicable to this design. From the plots, it can be seem that the best result is achieved when \( s_{ref} \) is set to be 2.29mm, which is equivalent to a quarter guide wavelength. The return loss is excellent and it also produces a very wide bandwidth. Therefore, for the last parameter, it can be considered a very sensitive parameter of the Quasi-Yagi antenna as it affects both the antenna’s design frequency and its operational bandwidth.

### 6.1.6 Final Design

As a result of the investigations on the sensitivity analysis of the Quasi Yagi antenna, the following dimensions have been determined for an antenna with relative dielectric constant of 10.2, substrate thickness of 0.635mm and a design frequency of 12.5GHz.

- Length of Director = 3.8mm
- Distance between Director and Driver = 2mm
- Distance between Coupled Microstrip Lines = 0.3mm
- Length of Driver = 8.17mm
- Distance from Driver to Reflector = 2.29mm

Shown below is the final design of the Quasi-Yagi antenna drawn on IE3D.

![Schematic Diagram of Quasi-Yagi antenna from IE3D](image-url)
6.2 Simulation Results of Quasi-Yagi Antenna

6.2.1 $S_{11}$ Return Loss and Bandwidth

Using the calculated dimensions, the design is simulated in IE3D from 9GHz to 16GHz. The achieved $S_{11}$ return loss of the Quasi-Yagi antenna is shown below in figure 6.3.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$\text{dB}(S_{11})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>-7.477</td>
</tr>
<tr>
<td>9.5</td>
<td>-12.92</td>
</tr>
<tr>
<td>10</td>
<td>-9.201</td>
</tr>
<tr>
<td>10.5</td>
<td>-17.37</td>
</tr>
<tr>
<td>11</td>
<td>-22.91</td>
</tr>
<tr>
<td>11.5</td>
<td>-23.26</td>
</tr>
<tr>
<td>12</td>
<td>-26.22</td>
</tr>
<tr>
<td>12.5</td>
<td>-27.25</td>
</tr>
<tr>
<td>13</td>
<td>-21.25</td>
</tr>
<tr>
<td>13.5</td>
<td>-21.93</td>
</tr>
<tr>
<td>14</td>
<td>-10.64</td>
</tr>
<tr>
<td>14.5</td>
<td>-10.13</td>
</tr>
<tr>
<td>15</td>
<td>-5.208</td>
</tr>
<tr>
<td>15.5</td>
<td>-2.903</td>
</tr>
<tr>
<td>16</td>
<td>-2.457</td>
</tr>
</tbody>
</table>

Figure 6.3: $S_{11}$ Return Loss of Quasi-Yagi Antenna
From the gathered results, it can be seen that the return loss is about –27.26dB at the design frequency of 12.5GHz, which can be considered acceptable. As for the bandwidth of the antenna, it is defined as the frequency range over which $S_{11}$ is less than or equal to –10dB. The bandwidth can be calculated using the following equation:

$$BW = \frac{(f_2 - f_1)}{f_0} \times 100\%$$

where $f_0$ is the centre frequency or the frequency where $S_{11}$ is minimum

$f_1$ and $f_2$ are the frequencies at which $S_{11}$ equals –10dB

Applying the above-mentioned equation, the calculated bandwidth of the Quasi-Yagi antenna is approximately about 36%. This accomplishment can be considered satisfactory, as the primary objective of achieving wide bandwidth at high frequencies for the Quasi-Yagi antenna has been met.

### 6.2.2 Voltage Standing-Wave Ratio

As for the Voltage Standing-Wave Ratio (VSWR), it is defined as a measurement of the mismatch between the load and the transmission line. Therefore, the simulated VSWR for the design of the Quasi-Yagi antenna is shown below in figure 6.4.

<table>
<thead>
<tr>
<th>Freq[GHz]</th>
<th>Port 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>2.465</td>
</tr>
<tr>
<td>9.5</td>
<td>1.584</td>
</tr>
<tr>
<td>10</td>
<td>2.061</td>
</tr>
<tr>
<td>10.5</td>
<td>1.313</td>
</tr>
<tr>
<td>11</td>
<td>1.154</td>
</tr>
<tr>
<td>11.5</td>
<td>1.148</td>
</tr>
<tr>
<td>12</td>
<td>1.103</td>
</tr>
<tr>
<td>12.5</td>
<td>1.091</td>
</tr>
<tr>
<td>13</td>
<td>1.119</td>
</tr>
<tr>
<td>13.5</td>
<td>1.188</td>
</tr>
<tr>
<td>14</td>
<td>1.265</td>
</tr>
<tr>
<td>14.5</td>
<td>1.097</td>
</tr>
<tr>
<td>15</td>
<td>3.435</td>
</tr>
<tr>
<td>15.5</td>
<td>6.34</td>
</tr>
<tr>
<td>16</td>
<td>7.118</td>
</tr>
</tbody>
</table>
Chapter 6: Results and Discussion

6.2.3 Impedance Smith Chart and Average Current Density

From the plot, it can be seen that VSWR < 2 at about 10.5GHz - 14.5GHz. This result showed that between the range of 10.5GHz and 14.5GHz, the VSWR of the antenna can be considered desirable as it is less than 2. However, when the design frequency is increased from 15GHz onwards, the VSWR tends to become worse, as can be seen from the plot. In other words, the line and the load tend to become more mismatched as the design frequency is increased from 15GHz onwards.

Figure 6.5: Impedance Smith Chart of Quasi-Yagi Antenna
Figure 6.5 on the previous page shows the impedance Smith chart obtained for the Quasi-Yagi antenna. For the plot, it shows that most of the points are located at the middle of the circle. Hence, this indicates that the matching of this antenna is quite good, as the desired location of the points should be in the middle of the circle (50Ω). In addition, the average current density of the antenna at 12.5GHz is shown in figure 6.6 below.

Figure 6.6: Average Current Density at 12.5GHz.
6.2.4 Radiation Patterns of Quasi-Yagi Antenna

Figure 6.7: 2D Polar Pattern of Quasi-Yagi Antenna

Figure 6.8: 2D Radiation Pattern of Quasi-Yagi Antenna
Figure 6.9: 3D Radiation pattern of Quasi-Yagi Antenna
Figure 6.10: 3D Mapped Pattern of Quasi-Yagi Antenna

Parameters at 12.5 GHz

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum at (145, 90) degrees</td>
<td></td>
</tr>
<tr>
<td>3dB Beam Width = 72.0563 degrees</td>
<td></td>
</tr>
<tr>
<td>The Directivity: 5.99772 (dB)</td>
<td></td>
</tr>
<tr>
<td>Mismatch Loss: -0.0081603 (dB)</td>
<td></td>
</tr>
<tr>
<td>Circular Polarization Loss: -2.16826 (dB)</td>
<td></td>
</tr>
<tr>
<td>Efficiency: 22.2045% (-6.53856 dB)</td>
<td></td>
</tr>
<tr>
<td>Total Radiated Power: 0.00221623 (W)</td>
<td></td>
</tr>
<tr>
<td>Average Radiated Power: 0.000176366 (W/s)</td>
<td></td>
</tr>
<tr>
<td>Input Power at Ports: 0.000998123 (W)</td>
<td></td>
</tr>
</tbody>
</table>

Figures 6.7 - 6.10 in the previous pages are the radiation patterns achieved by the Quasi-Yagi antenna at the design frequency of 12.5GHz. The values shown above are the radiation parameters of the antenna obtained at 12.5GHz.
CHAPTER 7

SUMMARY AND FUTURE PROSPECTS

This chapter concludes with a summary for the work done for this thesis and the future prospects of the Quasi-Yagi antenna and the Linearly Tapered Slot antenna. A rundown on the topics covered during this thesis is presented, including a sensitivity analysis on the Quasi-Yagi antenna. Subsequently, the future prospects of microstrip antennas, especially broadband planar antennas, have been addressed.

7.1 Summary

Microstrip antennas have been receiving much attention over the past few years due to its many conventional valuable properties like low-profile, light-weight, robust and
reasonably cheap to manufacture. As a result, microstrip antennas have been used extensively in microwave systems and wireless communication applications. Although the microstrip antenna suffers from some serious drawbacks like narrow frequency bandwidth and low efficiency, the performance of microstrip antenna elements and arrays has been constantly enhanced through the years. Many different forms of microstrip antennas have been developed over the years and in this thesis, two types of broadband planar antennas have been analyzed for used in spatial power combining.

In this thesis, both the Quasi-Yagi antenna and the Linearly Tapered Slot antenna have been analyzed both theoretically and experimentally through computer simulations. Detailed characteristics of the two types of antennas are presented, including their advantages, disadvantages and individual radiation characteristics. In addition, the design procedures for both the planar antennas were also investigated and presented. In chapter 5, the design guidelines and considerations for both the antennas have been shown, including all the calculations for both the antennas’ dimensions. The antennas are to be fabricated with a high dielectric constant substrate material (Duroid with dielectric constant $\varepsilon_r$) with substrate thickness of 0.635mm.

On the other hand, a sensitivity analysis of the Quasi-Yagi antenna has been performed for a substrate of dielectric constant of 10.2 and thickness of 0.635mm at the design frequency of 12.5GHz. The effects of the five parameters on its operational frequency and impedance bandwidth are investigated and the parameters most affecting the performance of the antenna are also identified. The results of the analysis revealed that all of the parameters would definitely affect the antennas’ performance in terms of return loss and operational frequency. However, the most sensitive parameters would be the length of the driver, director and the distance from the driver to the reflector. The length of the driver should most preferably be 1mm less than the guide wavelength $\lambda_G$. The length of the director should also be approximately half of the length of the driver. Lastly, for the distance from the driver to the reflector, it should be about a quarter guide wavelength. Comparing this observation to the results obtained in [23], it can be seen that there are some dissimilarity in the sensitivity analysis of the Quasi-Yagi antenna. The reason for the dissimilarity might be due to the difference in dielectric
constant and substrate thickness of the material used to fabricate the Quasi-Yagi antenna.

Therefore, taking into account of the results of the sensitivity analysis, the full-wave (MoM) method of moment analysis package IE3D of Zeland Software Inc. is used to analyze the performance of the Quasi-Yagi antenna. The simulation results showed that the antenna is able to achieve a simulated 36% frequency bandwidth for voltage standing-wave ratio VSWR < 2 at the centre frequency of 12.5GHz. In addition, the impedance smith chart showed an acceptable matched load to the transmission line. Last but not least, the average current density, radiation patterns, radiation parameters achieved at 12.5GHz are also presented.

As for the limitations encountered during the design process of the two antennas, the analysis of Linearly Tapered Slot antennas can be considered very complex due to its large size. As a result, the performance analysis of the LTSA is not done as the program IE3D could not support such a large and complex structure. In addition, the simulations for the Quasi-Yagi antenna have also been slow due to its complex structure and numerous calculations involved. Despite that, a sensitivity analysis of the Quasi-Yagi antenna has been performed and presented in this thesis.

### 7.2 Future Prospects

The microstrip antenna has been a huge phenomenon over the past few years. Although much efforts have gone into researches on designing the microstrip antenna, there appears to be no definite design procedures and formulations at present. The reason for this is because of the homogeneous nature of the microstrip structure. In other words, it is extremely difficult to analyze the electromagnetic fields generated by the microstrip antenna. Although some analysis methods have been presented in this thesis, these methods are not necessarily precise and might not achieve accurate results. Hence, it would be ideal if the design strategy of microstrip antennas could be well documented.
in the distant future so that microstrip antennas will eventually replace the large conventional microwave antennas in most applications.

Both the Quasi-Yagi antenna and the Linearly Tapered Slot antenna have proven to be an effective component for use in spatial power combining. Both the antennas possess many attractive features such as wide bandwidth and end-fire radiation characteristics. In addition, the Quasi-Yagi antenna also has a smaller size compared to the LTSA. Thus, with further improvements and researches, both these antennas would be very useful in applications like wireless communications systems, phased arrays, power combining and millimeter-wave imaging arrays.
References


