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Design, Simulation and Testing of Rectangular Microstrip Antennas

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Abstract

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The thesis focuses on the principles governing and explaining the operation of rectangular microstrip antennas. Microstrip antennas are comprised of metallic microstrips printed on circuit boards and are utilized in technologies where small volume, low cost, and ease of fabrication are preferred.

The presented antenna theory was applied in practical work, in which several different types of rectangular microstrip antennas with a theoretical resonant frequency of 869 MHz were designed, fabricated, and tested. Quarter-wave transformation, lumped element matching, and antenna shortcutting were utilized to improve the performance and impedance matching of the crafted antennas.

The specific resonant frequency was chosen so that the manufactured antennas could be in used in teaching during a course on Electromagnetic Compatibility at the Metropolia University of Applied Sciences. One of the course assignments requires students to build a radio transceiver system for transmitting and receiving a modulated 100 Hz square wave signal on the ISM band.

The input impedance, resonant frequency, reflection coefficient, and bandwidth of all the antennas were analyzed, and their influence on the antenna performance was reflected. A microstrip antenna with the desired resonant frequency was successfully fabricated and verified through laboratory testing.

Keywords: microstrip antenna, transmission line, microstrip line, rectangular patch antenna

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Tämä opinnäytetyö käsitteli suorakulmaisten mikroliuska-antennien teoriaa, suunnittelua, simulointia ja testausta. Mikroliuska-antennit rakentuvat piirikortille painetuista metallisista mikroliuskoista. Antenneja hyödynnetään teknologioissa joissa etusijalla ovat antennin pieni tilavuus, edullinen valmistuskustannus ja valmistuksen vaivattomuus.

Työn käytännön osuus keskittyi 869 MHz:n resonanssitaajuuden omaavan mikroliuska-antennin kehittämiseen. Antennia oli tarkoitus hyödyntää opiskelijatyössä Metropolian kurssilla *Sähkömagneettinen yhteensopivuus*. Kurssilla opiskelijat valmistavat radiolähettimen ja -vastaanottimen, ja käyttävät rakentamaansa systeemiä välittääkseen 100 Hz:n kanttiaallon langattomasti antennilta toiselle 869 MHz:n taajuudella. Taajuus 869 MHz on osa vapaata ISM-radiotaajusalueetta, jota käytetään teollisilla, tieteellisillä ja lääketieteellisillä sähkölaitteilla.

Tutkielman tarkoituksena oli esitellä mikroliuska-antennien suunnittelun kannalta kriittiset vaiheet, minkä jälkeen työssä demonstroitiin kaksi vaihtoehtoista tapaa toteuttaa ja sovittaa mikroliuska-antenni. Valmistetut antennit olivat ns. tavallisia suorakulmaisia mikroliuska-antenneja ja oikosuljettuja antenneja. Antennien suorituskyvyn ja impedanssin sovituksen parantamisessa hyödynnettiin neljännesaaltomuunnosta ja sovituspirejä.

Valmistettujen antennien sisääntuloimpedanssia, resonanssitaajuutta, heijastuskeroa ja kaistanleveyttä analysoitiin laboratoriomittauksilla ja simuloinneilla, ja niiden vaikutusta antennien suorituskykyyn pohdittiin. Työn lopputulos kattoi yhdeksän valmistettua antennia, joista yhden resonanssitaajuus oli noin 869 MHz. Kyseinen antenni toimi odotetusti ja saavutti hyvän suorituskyvyn taajuusalueellaan. Antennia voidaan hyödyntää opetuksessa.

Avainsanat: mikroliuska-antenni, piirilevyantenni, antennin siirtolinja

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Appendix 1: Formulas for Microstrip Antenna and Microstrip Line Design

Appendix 2: Maxwell's Equations and Lorentz Force Law

List of Abbreviations

- AM: Amplitude Modulation. Method for encoding information in radio signals by varying carrier wave amplitude in proportion to the transmitted signal.
- AWR: Applied Wave Research. A suite of electronic design automation tools used for the design, simulation, and analysis of radio-frequency, microwave, and high-frequency circuits and systems.
- DUT: Device Under Test. The device being tested to evaluate its performance.
- FM: Frequency Modulation. Method for encoding information in radio signals by varying carrier wave frequency in proportion to the transmitted signal.
- FR-4: Flame Retardant 4. A substrate material made of woven fiberglass cloth with an epoxy resin binder that is flame resistant and used in the production of printed circuit boards.
- GPS: Global Positioning System. A satellite-based navigation system that provides location and time information.
- HF: High Frequency. Range of frequencies from 3 to 30 MHz.
- ISM: Industrial, Scientific, Medical band. Frequency band which has been designated for use in industrial, scientific, and medical applications.
- MoM: Method of Moments. A numerical computational technique used to solve integral equations, often applied in electromagnetic field problems.

- MSA: Microstrip Antenna. An antenna constructed on a printed circuit board using microstrip lines.
- PCB: Printed Circuit Board. A substrate plate on which electric components are connected to each other by metallised lines and patches.
- RF: Radio Frequency. Frequencies spanning from 3 kHz to 300 GHz.
- RFID: Radio Frequency Identification. A technology based on electromagnetic fields and used for identifying and tracking tags attached to objects.
- SMA: SubMiniature version A. A coaxial radio frequency connector.
- UHF: Ultra High Frequency. Range of frequencies from 300 MHz to 3 GHz.
- VHF: Very High Frequency. Range of frequencies from 30 to 300 MHz.
- VNA: Vector Network Analyzer. Instrument used to measure reflection coefficients of electronic networks.
- VSWR: Voltage Standing Wave Ratio. A measure of how efficiently radio-frequency power is transmitted from a power source into a load.
- WLAN: Wireless Local Area Network. Wireless computer network.
- Wi-Fi: Wireless Fidelity. Technology that enables wireless communication between devices.

1 Introduction

This thesis concerns the properties of microstrip antennas (MSAs) and is a combination of background research and practical work with a focus on creating an optimal rectangular microstrip patch antenna with a resonant frequency of 869 MHz.

1.1 Background and Motivation

Antennas are instruments utilised in transmitting and receiving radio waves. They act as the conversion point between propagating electromagnetic waves and electric current. Antennas are an essential component of wireless communication systems as receivers, transmitters, or transceivers.

Presently wireless communication is expected of most intelligent consumer and industrial devices. Antenna based technologies include Wi-Fi, Bluetooth, GPS, and radar. Expertise of antennas is highly valued in the electronics industry and research into higher-performing antennas is thriving.

As the size of semiconductor devices continuously decreases due to the number of transistors doubling every two years according to Moore's law, the demand for compact antennas is high. Microstrip antennas are simple, low-cost, and low-profile antennas which can be fitted onto printed circuit boards (PCBs) with suitable optimization techniques. They are applied in trending commercial needs like wearable technology and Internet of Things. [1,1.]

1.2 Objectives of the Thesis

The purpose of the thesis was to give an overview of the principles involved in the design and testing of microstrip antennas. The aim of the practical work of this thesis study was to actualise a patch antenna with a resonant frequency of 869 MHz. The frequency was chosen according to a student laboratory

assignment in the Metropolia University of Applied Sciences' course *Electromagnetic Compatibility*. In the assignment, students build a radio transmitter and receiver system and study its use on the industrial, scientific, and medical (ISM) band. The patch antennas designed in the thesis work can be utilised in future instances of the course.

1.3 Scope and Limitations

This thesis focuses on microstrip antennas on an introductory and mostly theoretical level. The aim is to familiarise with the topic and its applications. For the non-expert reader, this text is meant to be an introduction to the topic.

The thesis does not delve deep into the mathematics and physics behind antennas. Basic formulas relating to key concepts and results are presented, but otherwise, the text focuses on generalised ideas in the field of antennas. The methods described in the practical work are easy to replicate with appropriate equipment.

1.4 Organization of the Thesis

The content is organized into nine chapters. The first chapter introduces the topic and the objectives of the thesis. The second chapter is a background survey of antennas in general, with the intention of presenting their key concepts and paving the way for discussion about microstrip antennas.

The third chapter focuses on the fundamentals of microstrip antennas and advances to the fourth chapter on the design methods of microstrip patch antennas. The fifth chapter presents different approaches to evaluating the performance of microstrip antennas. Testing of microstrip patch antennas is the subject of the sixth chapter, with the seventh chapter analysing the results of fabricated antennas. The eighth chapter introduces microstrip antenna simulations. Finally, the ninth chapter gathers conclusions and suggests recommendations for future work.

2 Fundamentals of Antennas

The foundation of microwave and antenna engineering is in electromagnetics. In this chapter, the basics of electromagnetic fields and the electromagnetic spectrum are covered. The focus then shifts to the working principles of antennas, giving an overview of the various antenna types, and finally introducing microstrip antennas.

2.1 Electric and Magnetic Fields

Electromagnetics is the study of electric and magnetic fields. Antennas radiate electromagnetic waves which form the basis of wireless communication. The theory of electromagnetism is captured by Maxwell's Equations and Lorentz Force Law in Appendix 2.

Electric fields are created by charged particles. The electric field of a point charge (\vec{E}) is described by Coulomb's Law in Equation (1) where ϵ_0 is the permittivity constant, q point charge, r the distance between the field and the charge, and \hat{r} unit vector which determines the direction of the electric field. [2,809.]

$$\vec{E} = \frac{1}{4\pi\epsilon_0} \frac{q}{r^2} \hat{r} \quad (1)$$

Magnetic fields are created by moving charged particles or changing electric fields. The magnetic field of a point charge (\vec{B}) is described by the Biot-Savart Law in Equation (2) where μ_0 is the permeability constant, q point charge, r the distance between the field and the charge, \vec{v} the velocity of the charge, and \hat{r} the unit vector pointing to the direction of the magnetic field. [2,1003.]

$$\vec{B} = \frac{\mu_0}{4\pi} \frac{q\vec{v} \times \hat{r}}{r^2} \quad (2)$$

Once an electromagnetic wave is created by charges and currents, it becomes self-sustaining since a changing magnetic field creates an electric field by induction, which in turn recreates the original magnetic field. This relationship is described by Faraday's and Ampère-Maxwell Laws in Appendix 2. [2,1096-1097.]

2.2 Electromagnetic Spectrum

The electromagnetic spectrum is divided into seven different radiation types according to wavelength and frequency: radio waves, microwaves, infrared radiation, visible light, ultraviolet, x-rays, and gamma rays. Electromagnetic waves are composed of electric and magnetic fields [3,3]. An illustration of the different radiation types of the electromagnetic spectrum is shown in **Error! Reference source not found..**

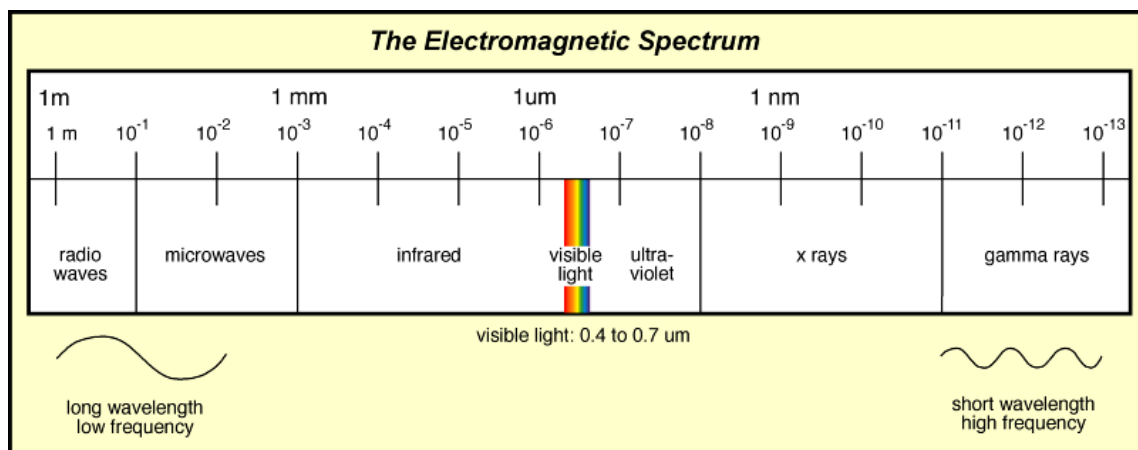


Figure 1. The electromagnetic spectrum with wavelengths [4].

Antennas can transmit and receive radio waves, microwaves, infrared radiation, and visible light but only the first two types of radiation are frequently used in applications. Radio waves are typically classified as electromagnetic radiation with a frequency less than 300 GHz. The wavelength of a radio wave varies between 10 000 kilometres at the low frequencies and one metre at the high frequencies. Microwaves are a subcategory of radio waves with frequencies beginning at 1 GHz and ending in 300 GHz. [5.]

In Table 1, the band designation of radio wave spectrum along with its example uses is shown. The ISM band is a collection of frequency bands that can be freely used by industrial, scientific, and medical devices without having to compete with already established users such as the defence sector [6]. The Finnish Transport and Communications Agency has defined the open frequency bands in Finland in their Radio Frequency Regulation 4AE/2024M. The 2 MHz frequency band from 868 MHz to 870 MHz is reserved for general short-range transmitters and is of special interest in this thesis. [7.]

Table 1. Frequency band designations of radio waves, wavelengths and example uses [3,11].

Band Designation	Frequency	Wavelength	Example Uses
ELF (Extremely Low Frequency)	3 to 30 Hz	100 to 10 Mm	
SLF (Super Low Frequency)	30 to 300 Hz	10 to 1 Mm	Power lines
ULF (Ultra Low Frequency)	300 to 3 kHz	1 Mm to 100 km	
VLF (Very Low Frequency)	3 to 30 kHz	100 to 10 km	Submarine communication
LF (Low Frequency)	30 to 300 kHz	10 to 1 km	Radio Frequency Identification (RFID)
MF (Medium Frequency)	300 kHz to 3 MHz	1 km to 100 m	Amplitude Modulation (AM) broadcast
HF (High Frequency)	3 to 30 MHz	100 to 10 m	Shortwave broadcast
VHF (Very High Frequency)	30 to 300 MHz	10 to 1 m	Frequency Modulation (FM) and TV broadcast
UHF (Ultra High Frequency)	300 MHz to 3 GHz	1 m to 10 cm	TV, WLAN, GPS, Microwave ovens

Band Designation	Frequency	Wavelength	Example Uses
SHF (Super High Frequency)	3 to 30 GHz	10 to 1 cm	Radar, WLAN, Satellite communication
EHF (Extremely High Frequency)	30 to 300 GHz	10 to 1 mm	Radar, Radio astronomy, Point-to-point high-rate data links, Satellite communication
Microwaves	1 to 300 GHz	30 cm to 1 mm	
Millimetre waves	30 to 300 GHz	10 to 1 mm	
Submillimetre waves	>300 GHz	<1 mm	

2.3 Working Principles of Antennas

Signal carrying techniques, antenna fields and antenna properties explain the essentials of antenna operation. These topics are discussed in the following chapters.

2.3.1 Signal Carrying Techniques

An electric signal can be transferred between locations by either via a physical transmission line or from one antenna to another via empty space. Transmission lines encase electromagnetic waves inside or near them, whereas antennas spread them in air through radiation. [3,10.]

Radio frequency engineering is needed when the transmission lines of a circuit board are approximately one tenth or more of the wavelength they are used to transmit. At this scale transmissions begin to have issues with reflections, impedance matching, and efficient propagation.

An antenna radiates electromagnetic waves in all directions away from itself, but the radiation pattern of an antenna is not uniform in all directions. When a transmitter and a receiver are placed within a distance r of each other, the power loss of a transmission line signal is described with $(e^{-\alpha r})^2$, where α is the attenuation constant of the transmission line. When a transmitting and a receiving antenna are placed within seeing distance r of each other, the signal power loss is proportional to $\frac{1}{r^2}$.

For low frequencies and distances, the transmission line is generally the best option. But for high frequencies and distances, the power loss of transmission line increases as do the expenses of manufacturing and using a transmission line. In these cases, the use of less costly antenna is preferred. [3,12.]

The working mechanism of an antenna is simplified in Figure 2, where an electromagnetic wave is shown travelling on the transmission line to the port of a transmitting antenna named Antenna 1. The antenna converts the power from the transmission line to an electromagnetic wave that propagates in free space towards Antenna 2. Antenna 2 is a receiving antenna that captures power from the propagating wave and supplies it to a transmission line through Port 2.

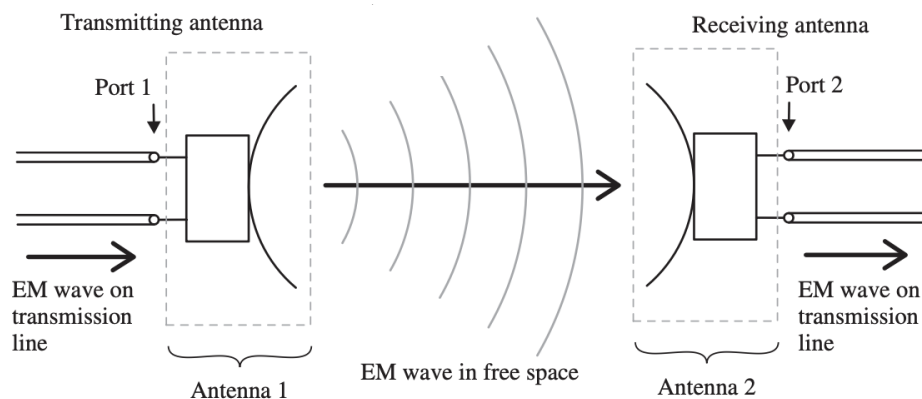


Figure 2. Antenna transmission and receiving [8,250].

2.3.2 Near and Far Field

The electromagnetic fields originating from an antenna are observed either at a proximity to the antenna or at a considerable distance from it. The previous is described as the near field and the latter as far field of the antenna. Typically, the far field is of greater interest as communicating antennas are located at a distance from each other.

The near field has a more complex field distribution when compared to the far field where the wavefronts are spherical. The far field distance (r) is defined by the wavelength of the operational frequency and the geometry of the antenna. In electrically small antennas such as microstrip antennas, it is described by Equation (3) where the far field distance is at least twice the wavelength. [8,249-251.]

$$r \geq 2\lambda \quad (3)$$

2.3.3 Characteristics of Antennas

The performance of antennas is evaluated according to parameters such as radiation pattern, directivity, radiation efficiency, polarization, input impedance, and bandwidth.

The radiation pattern describes the distribution of radiated energy in the space surrounding the antenna, whereas directivity is a measure of the radiation intensity for a given direction pointing outwards from the antenna. An isotropic antenna radiates uniformly in all directions from the antenna. [9,27;3,44.]

Antenna efficiency characterises the losses occurring at the input and at the antenna when power is fed to the antenna. Gain or radiation efficiency is the intensity ratio between the measured intensity in a given direction and the intensity of an isotropic antenna, which is equal to the input power of the antenna. [9,64-66.]

Polarization of an antenna refers to the polar angle of the transmitted electromagnetic wave. If no direction is defined, the direction of maximum gain is chosen by default.

The input impedance of antenna is a measure of the antenna's opposition to the flow of alternating current. Impedances of antenna system must be matched to maximize the efficiency of the antenna.

The bandwidth of an antenna is the frequency range in which the antenna's performance is acceptable. This means that the characteristics of antennas, such as the input impedance and gain, are within specified limits. There is no uniform standard according to which the bandwidth of an antenna is defined. It is usually a range defined by the manufacturer of the antenna. The designer must determine whether the characteristic values of an antenna suit the needs of a specific application. [9,70-71.]

2.4 Overview of Antenna Types

A great number of antenna designs exist, and antennas can be classified in various ways. One useful way to sort them into categories is to examine them in terms of their performance characteristics. Based on their performance four different antenna classes can be defined: electrically small, resonant, broadband, and aperture antennas.

Electrically small antennas have a simple design and a size that is significantly smaller than the wavelength of the transmitted and received electromagnetic wave. They often have omnidirectional radiation patterns on the horizontal plane, meaning that they cover multiple directions. Small antennas are used in frequencies reaching up to very high frequency (VHF). The disadvantages include low radiation efficiency, input impedance and directivity. Two examples of electrically small antennas, a short dipole and a small loop antenna, are shown in Figure 3.

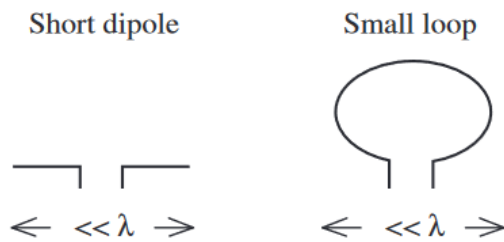


Figure 3. Diagrams of a short dipole and a small loop antenna [3,20].

Similarly to electrically small antennas, resonant antennas have a simple and compact structure, usually spanning half of the size of the signal wavelength. However, unlike small antennas, their input impedance is real, and they are optimised for use at a single frequency or a very narrow bandwidth. Their detriment is a low to moderate gain. They are used at frequencies spanning from high frequency (HF) to low gigahertz. The microstrip patch antenna, along with a half-wave dipole and Yagi antennas, are examples of resonant antennas as illustrated in Figure 4.

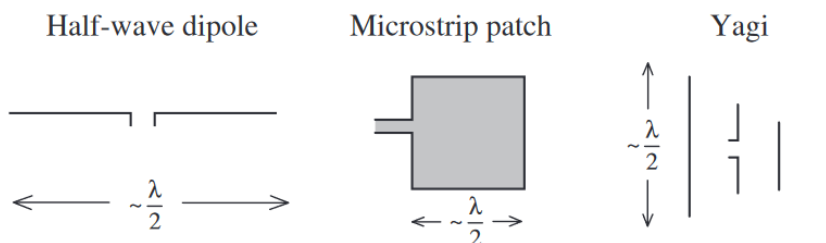


Figure 4. Diagrams of half-wave, microstrip patch and yagi antennas [3,20].

The active region from which the power is radiated in broadband antennas is approximately the size of the signal's wavelength. Broadband antennas are capable of operating on wide frequency bands, and the active region travels on the antenna depending on the operation frequency. The operation frequency varies between VHF and middle gigahertz frequencies. Due to the small size of the active region, gain is moderate yet constant. The input impedance is real, making the antenna easy to match. Two examples of broadband antenna designs are shown in Figure 5.

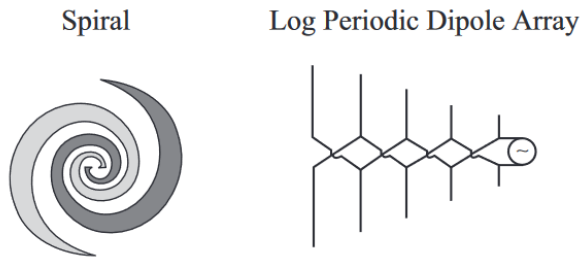


Figure 5. Diagrams of a spiral and a log periodic dipole array antenna [3,20].

Aperture antennas have an opening in their structure through which electromagnetic waves propagate. The opening is typically several wavelengths long. The advantage of the design is that the gain is high, and it increases with frequency. On the other hand, the bandwidth is moderate, and the design more complex than electronically small and resonant antennas. Aperture antennas operate at the ultra-high frequency (UHF) and above. The horn and reflector antennas shown in Figure 6 are common examples of aperture antennas. [3,19-20.]

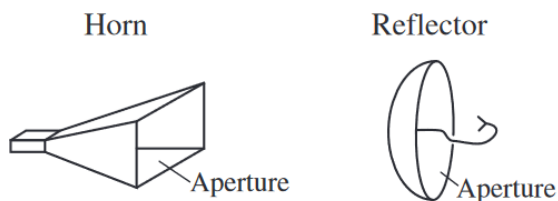


Figure 6. Two examples of an aperture antenna: a horn and a reflector antenna [3,21].

2.5 History and Evolution of Microstrip Antennas

The microstrip antenna was first patented in 1953, but research into them did not gain vigour until the 1970s, culminating in the first extensive article *Microstrip Antenna Technology* by K. Carver and J. Mink in 1981.

The applications of the first microstrip antennas were few due their narrow bandwidth. New feed mechanisms were designed to increase their bandwidth in the 1980s, and in the 1990s, commercial applications began to embrace them.

These days, microstrip antennas appear as isolated antennas and array elements. Their use is preferred in base station antennas and position location devices such as GPS in cars. [3,467-468;9,812.]

2.6 Introduction to Microstrip Antennas

A microstrip antenna is a thin metallized patch printed on a grounded dielectric substrate. The thicknesses of the patch (t) and the substrate (h) are at least significantly smaller than the free-space wavelength of the signal frequency. The substrate has a specific dielectric constant (ϵ_r), which describes the material's capability of storing electrical energy in an electric field. A rectangular microstrip antenna is shown in Figure 7.

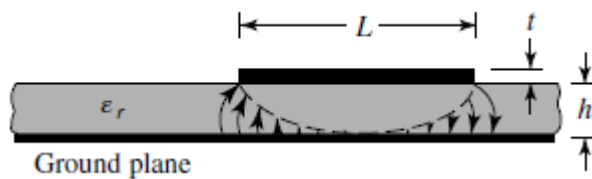


Figure 7. Sideview structure of a rectangular microstrip antenna [9,812].

Microstrip antennas are used in numerous applications due to their advantageous design. They are simple in structure; therefore, their fabrication is low-cost and fast. Their profile is small, and they can be fitted to tight spaces or curved surfaces. MSAs are resistant to shock and vibration and failures occur mostly at the feed probe solder joint. They can be easily integrated with other microstrip structures such as branchline hybrids for circular polarization.

MSAs main disadvantages include a narrow frequency bandwidth which is typically 5-10 %, and low antenna efficiency due to dielectric and conductor losses in thin patches. They are also sensitive to environmental factors such as temperature and humidity. They have a high-Q meaning that they are efficient in terms of converting electrical power to radiation at the resonant frequency. MSAs have a poor polarization purity indicating that they have a weakened ability to

maintain consistent polarization when transmitting or receiving signals. Also, they are difficult to adjust after manufacturing. [3,466;9,811;10,19.]

3 Fundamentals of Microstrip Antennas

The functionality of a microstrip antenna is largely determined by the combination of the substrate material, feeding mechanism, and matching of the signal source to the antenna.

3.1 Substrate Materials and Dielectric Properties

Microstrip antennas are printed on substrate material which provides mechanical support to the structure. The substrate also acts as an insulator between the antenna and the ground plane. The substrate's dielectric properties influence the antenna impedance and bandwidth. Variations in the thickness and uniformity of the substrate also influence the resonant frequency of a narrowband MSA.

The dielectric constants of the substrate materials are typically between 2.2 and 12 in microstrip antennas [9,812]. Some of the commonly used substrate materials and their dielectric constants are listed in Table 2. Flame Retardant 4 (FR-4) is a low-cost material with high losses and is therefore rarely used at frequencies over a couple of GHz. By increasing the dielectric constant of the substrate material, the antenna size can be reduced while maintaining enough bandwidth for GPS use. Barium titanate is an example of a substrate material which has a high dielectric constant [3,468.]

Table 2. Dielectric materials for microstrip antennas [3,468;10,283].

Name	Material group	Dielectric constant (ϵ_r)
Teflon	Polytetrafluorethylene (PTFE)	2.1
FR-4	Fiberglass with epoxy resin binder	4.1-4.6

Name	Material group	Dielectric constant (ϵ_r)
Barium titanate	Ceramics	7.0
Alumina	Ceramics	9.8

3.2 Feed Mechanisms and Matching Techniques

Microstrip antennas can be fed in various ways. The most common methods for patch antenna feeding are microstrip line, coaxial probe, aperture coupling, and proximity coupling [9,813]. Impedance matching is needed to reduce signal losses during transmission between different parts of electronic circuits. When a transmission line is connected to a resonating patch, impedance matching is necessary to transfer power efficiently to the antenna for radiating.

3.2.1 Microstrip Line

A microstrip feeding line can be connected either to the radiating or the nonradiating edge. When the feeding line is connected to the nonradiating edge, there is no need for impedance matching because the 50 Ω transmission line can be connected directly to the 50 Ω driving point impedance, as shown in Figure 8a and Figure 8b.

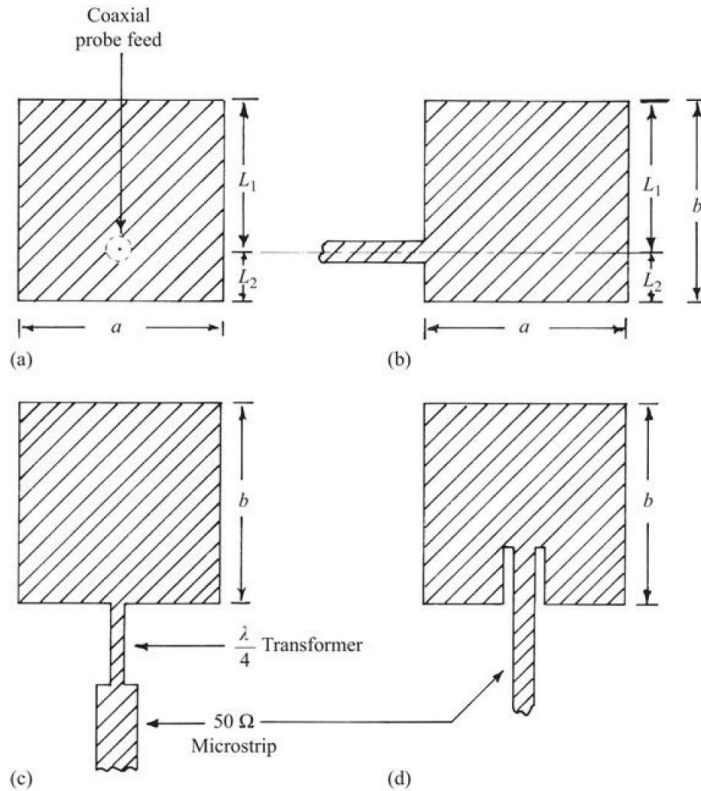


Figure 8. Feeding mechanisms for rectangular patch antenna [10,29].

Connecting the microstrip line to the radiating edge, as in Figure 8c, causes disturbances in the field distribution and influences the antenna's radiation pattern. Often, a quarter-wave transformation is adopted for impedance matching the transmission line with the antenna patch in systems of single frequency or small bandwidth. A quarter-wave transformer is a microstrip line placed in between the transmission line and the antenna. It has a length of one quarter of the signal's wavelength. [11.]

When the load impedance is real, the impedance of the quarter wavelength line is estimated with Equation (4).

$$Z_q = \sqrt{Z_0 Z_L} \quad (4)$$

Here, Z_0 is the impedance of the transmission line and Z_L the input impedance of the antenna. The microstrip line width and length to create a line with impedance Z_q can be calculated with microstrip line formulas in Appendix 1.

Another microstrip line feeding mechanism is to carve out a small area of the antenna patch and connect the transmission line directly to the $50\ \Omega$ feeding point from the side of the radiating edge, as in Figure 8d. This is called recessed microstrip-line feed. The downside is that the notch perturbs the electric fields fringing on the edge of the antenna. [10,28.]

3.2.2 Coaxial Probe Feed

In the coaxial probe feed method, a hole is drilled to the printed circuit board so that the coaxial transmission line passes through the ground plane and the substrate and connects to the antenna patch, as seen in Figure 9. Only the shield of the coaxial transmission line is connected to the ground plane.

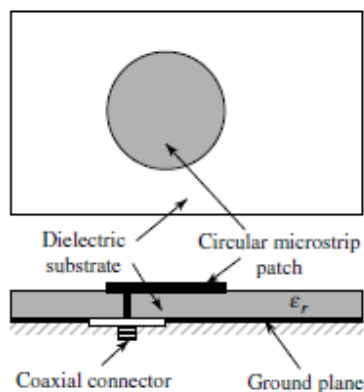


Figure 9. Coaxial feed structure [9,814].

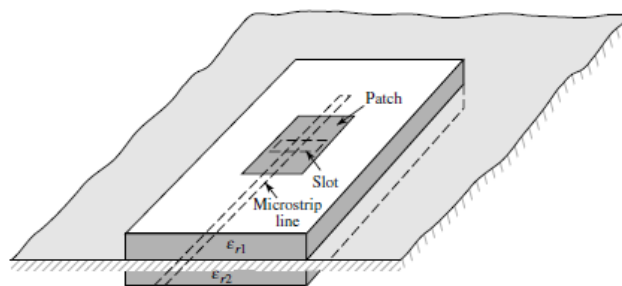
When the feed is in the centre of the patch lengthwise, the purest linear polarization is achieved. The coaxial probe feed is simple to fabricate and match, but it also has a narrow bandwidth, and it is difficult to model. [9,813;10,28.]

3.2.3 Aperture and Proximity Coupling

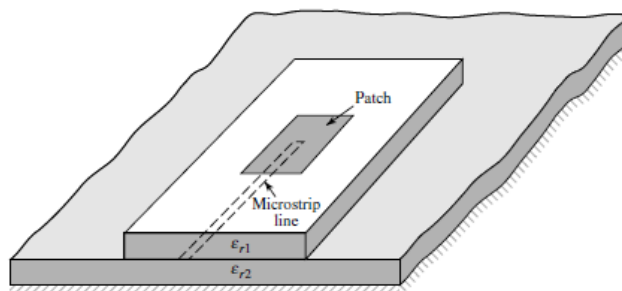
Aperture and proximity coupling are both noncontact feeding modes for patch antennas. They are more difficult to fabricate than the coaxial probe and microstrip line feeds, but there is also less stray radiation which improves pattern

formation and polarization purity. Illustrations of these modes can be seen in Figure 10.

In aperture coupling, two substrate plates are separated by a ground plane. An antenna patch is fabricated on top of one of the substrates while a microstrip line is placed on the opposite side of the structure. A slot is created on the ground plane between the substrates through which the feed and the radiating element couple.



(c) Aperture-coupled feed



(d) Proximity-coupled feed

Figure 10. Diagrams of noncontacting aperture coupling methods [9,814].

The proximity coupling is very similar to the aperture coupling method, except that the microstrip line is located between the substrates and the ground plane is on the other side of the structure. In this setup, there is no need to create a slot in the ground plane because the transmission line and antenna patch couple through a substrate plate. [9,814-815.]

4 Analytical Modelling Techniques

Analytical models for microstrip antennas were developed to simplify their behaviour and, most importantly, to predict their impedances for design

purposes. Two popular models, the transmission line model and the cavity model, are introduced to present how a patch antenna's performance is investigated.

4.1 Transmission Line Model

A rectangular microstrip antenna radiates along the edges of the antenna. The electric fields extend beyond the antenna structure, and these types of fringing fields are caused by spatial variation of electric potential near the edges of the antenna.

The structure of a rectangular patch antenna utilized in the transmission line model is shown in Figure 11. The substrate between the patch and the ground plane has a thickness of h . The patch has a width of $W = a$ and a length of $L = b$. The antenna radiates along the ends of the antenna, and the resonating edges have a distance L between them. In the illustration, the feeding point, i.e., the input point for microwave power is along the central line of the antenna, but the antenna can be modelled correspondingly as having a transmission line connected to one of the radiating edges.

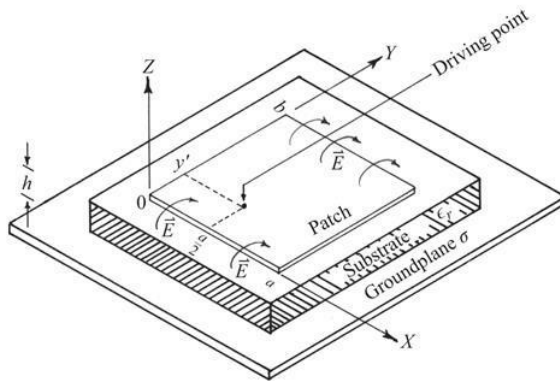


Figure 11. Rectangular patch antenna as seen by transmission line model [10,24].

Figure 12 shows, in the top diagram, how the transmission line model transforms the patch antenna of length $L = L_1 + L_2$ to a simplified construct of two terminating loads, which have their characteristic resistance G_e and reactance jB_e . The feeding point is located along the centre line between the edges of the

antenna with an impedance of Z_{drv} . The bottom diagram demonstrates how the antenna can be analysed as two edge admittances Y_e , which are separated by transmission lines with admittance Y_0 . The edge admittances model the radiation loss of the antenna.

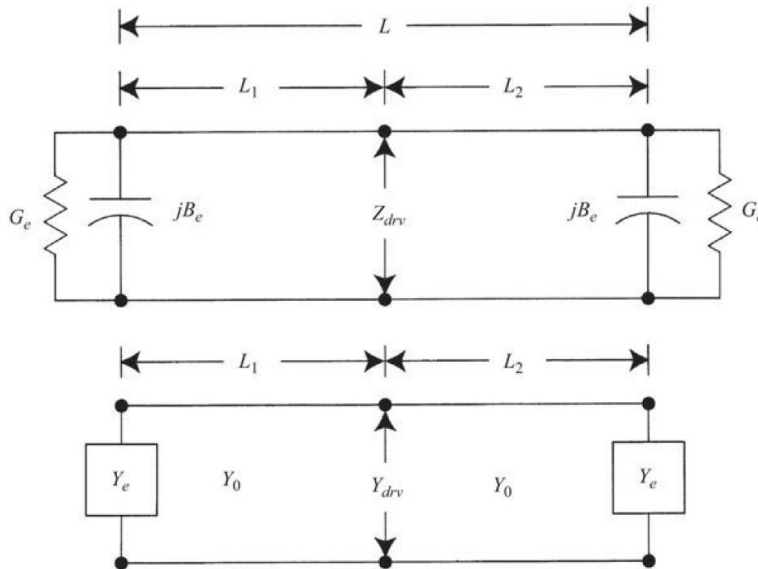


Figure 12. Transmission line model of a patch antenna with the feeding point located in between the radiating edges.

The transmission line model is easy to analyse, but this comes at the cost of inaccuracies in the impedance bandwidth when a thin substrate is used with the modelled antenna. [10,24-28.]

4.2 Cavity Model

The cavity model was developed to overcome the challenges of the transmission line model, which assumes that current flows only in one direction along the transmission line and does not account for nonlinear excitation modes.

A more precise calculation of the normalized fields within the dielectric substrate is enabled by treating the space between the patch and the ground plane as a cavity bounded by electric conductors above and below. Magnetic walls along the perimeter are employed to simulate an open circuit.

While an approximation, this model typically yields a reactive input impedance, either zero or infinite at resonance, and does not emit power. However, when the actual fields closely resemble those generated by this model, the computed pattern, input admittance, and resonant frequencies align well with experimental measurements. [9,826.]

5 Performance Analysis and Evaluation

The performance of a microstrip antenna can be evaluated according to its impedance, reflection coefficient, voltage standing wave ratio, resonant frequency, and bandwidth, among other characteristics. These traits are strongly linked to each other.

5.1 Antenna Impedance

Antenna input impedance is an important factor in building a communications system because matching the antenna impedance with the system impedance ensures that maximum power is transferred between them in transmission and receiving.

Antenna impedance can be measured between the terminals of an antenna with a vector network analyzer. Antenna impedance (Z_a) is made up of antenna resistance (R_a) and antenna reactance (X_a) as shown in Equation (5).

$$Z_a = R_a + jX_a \quad (5)$$

The real part of antenna impedance (R_a) is described by Equation (6), where it is split into conductive and dielectric losses (R_l) and radiation resistance (R_r).

$$R_a = R_l + R_r \quad (6)$$

Furthermore, radiation efficiency (e) in Equation (7) is the ratio between radiation loss and antenna resistance.

$$e = \frac{R_r}{R_r + R_l} \quad (7)$$

Antenna reactance is to do with the stored energy in the electrical and magnetic fields of the antenna. When the fields are equal, reactance is zero, and the antenna is in resonance. At resonance the antenna impedance only has a real part (R_a) and it can be matched easily with suitable transmission lines. In an ideal system, all the energy inputted to the antenna would radiate as radiation resistance. [12.]

5.2 Reflection Coefficient

Reflection coefficient describes the fraction of the incident signal which is reflected to the source from the load. S-parameters describe the electrical behaviour of radio frequency (RF) and microwave devices by relating the incident and reflected signals at the ports of the device. S_{11} is the reflection coefficient of port 1, which is the input port of the tested device. S_{11} is a complex number which has a magnitude and a phase. Equation (8) shows the mathematical expression for S_{11} .

$$S_{11} = \frac{V_{reflected}}{V_{incident}} \quad (8)$$

Typically, S_{11} is expressed in terms of its magnitude in decibels which indicates how much power is reflected back to port 1. The conversion to decibels is described by Equation (9).

$$|S_{11}|_{dB} = 20 \log_{10}(|S_{11}|) \quad (9)$$

5.3 Voltage Standing Wave Ratio

The voltage standing wave ratio (VSWR) is related to the reflection coefficient as shown by Equation (10). It is another measure of the reflection and impedance matching of the system.

$$VSWR = \frac{1+|S_{11}|}{1-|S_{11}|} \quad (10)$$

5.4 Resonant Frequency

At the resonant frequency, maximum power is transferred to the patch antenna as the optimal impedance matching between the feedline and the antenna is achieved. The impedance becomes completely resistive and the antenna efficiency peaks.

A patch antenna is commonly designed to be used at a specific frequency. The width and length of the patch are determined by that frequency because the antenna needs to reach resonance at it.

5.5 Bandwidth and Efficiency

Antenna bandwidth is the frequency range in which the efficiency of the antenna is at an acceptable level. Bandwidth can be increased by increasing the width of the antenna and the substrate thickness.

In many applications, the operational bandwidth is defined as the frequency range in which VSWR is less than or equal to 2. Another definition in use is that the magnitude of the reflection coefficient S_{11} in decibels is less than -10 dB.

6 Measurement and Testing

The testing of a microstrip antenna is crucial in insuring that it fulfils the specifications defined during the design phase. One of the most common instruments used in antenna testing is the Vector Network Analyser (VNA). It measures the impedances of an antenna in different frequencies and uses the results to determine the antenna's reflection coefficient, resonant frequency, and VSWR.

6.1 Vector Network Analyser

VNA measures devices by producing an RF incident signal which is fed to the input of the device under test (DUT) as a stimulus. The device reflects a portion of the signal back to the RF source and transmits the rest. If the DUT is passive, some of the signal may be lost in absorption and if it is active, the signal may be amplified. The diagram in Figure 13 illustrates the described setup. [13,3-3]

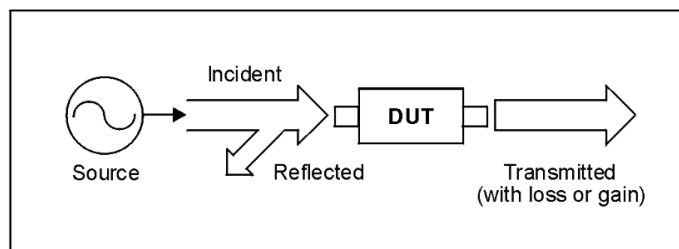


Figure 13. Device under test responding to a RF source stimulus. [13,3-3]

When the DUT is an antenna, only the reflection port of the VNA is used. The antenna is connected to the reflection port with a coaxial cable, and a RF signal is fed to the antenna. The VNA measures the impedance of the antenna, which is used to determine the reflection coefficient and VSWR.

6.2 Measuring Input Impedance

A MPA's input impedance is measured by connecting the feedline of the antenna to reflection port of a VNA via a coaxial cable. VNA outputs a signal from the reflection port to the antenna and measures how much of the outputted power is reflected to the port and how much is transmitted by the antenna via radiation. VNA does a frequency sweep and measures the same parameters at all the defined frequencies. From the sweep, the operating bandwidth, resonant frequency, and reflection are collected.

6.3 Electrical Delay

Electrical delay is defined as the time it takes for an electromagnetic wave to propagate through a transmission line or a device. The delay is caused by the finite propagation speed in the medium. The phase shift of a signal in radians is proportional to its frequency (f) and electrical delay (τ) as shown in Equation (11).

$$\phi = 2\pi f\tau \quad (11)$$

Electrical delay influences impedance measurements and therefore must be accounted for when calibrating a measurement instrument such as a VNA.

7 Project Results

The aim of the practical work was to fabricate a rectangular microstrip antenna with a resonant frequency of 869 MHz. The feed was realized as a microstrip line. Two different designs were realised and tested: a typical rectangular patch antenna and a shorted rectangular patch antenna. Also, two different matching techniques were utilised: a quarter-wave transformer and a lumped element circuit.

In the thesis work, the required specifications for the manufactured antennas were that the VSWR was less than or equal to 2, the reflection coefficient in dB was less than -10 dB and that the resonant frequency was within the bandwidth which fulfilled the first two conditions.

7.1 Rectangular Patch Antenna

The designed rectangular patch antennas were fabricated and tested. After testing, quarter-wave transformer and lumped element matching were applied to improve impedance matching.

7.1.1 Fabrication

The Equations (1), (2) and (3) in Appendix 1 were used to calculate the physical dimensions of a patch antenna with a resonant frequency (f_0) of 869 MHz. FR-4 was utilised as the substrate material, and it had a dielectric constant (ϵ_r) of 4.2 and a height (h) of 1.5 mm. The thickness of the PCB copper layer was 36 μm . With these parameters, the size of the antenna patch was calculated to be 84 mm in length (L_A) and 107 mm in width (W_A).

The microstrip line was required to have an input impedance of 50 Ω and an electrical length of 90 degrees to ensure that matching the generator with the load would be seamless. The microstrip line had a calculated width (W_L) of 2.97 mm (see Equations (4)-(9) in Appendix 1) and the length (L_L) was chosen to be 20.0 mm for convenience as it had no significant effect on the line impedance.

The antennas were designed with Cadence AWR Microwave Office software. The designed antenna was then milled on a two-sided copper plate based on the Gerber files produced by AWR. A SubMiniature version A (SMA) connector was soldered to the end of the microstrip line. The centre pin of the connector was soldered to the microstrip line while the outside sleeve was soldered to the ground plane as seen in Figure 14.

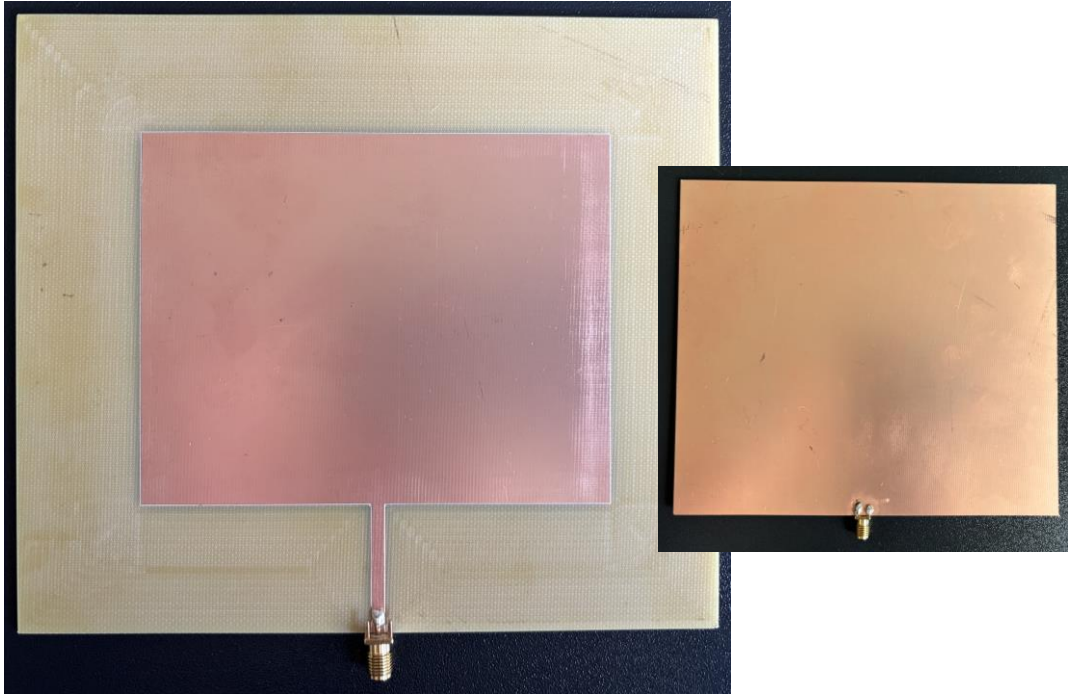


Figure 14. The first milled rectangular microstrip antenna. The left picture is of the topside and the right of the bottom ground plane of the antenna.

Two more rectangular patch antennas were milled to find the optimal antenna size for the chosen resonant frequency. Their fabrication was identical to the first antenna described in this chapter. Varying the length of the antenna affected the input impedance of the antenna and furthermore the resonant frequency. As the antenna patch was shortened, the resonant frequency increased. The sizes of the antenna patch variants are listed in Table 3.

7.1.2 Testing

The fabricated rectangular antennas were connected to the reflection port of a calibrated vector network analyser via a coaxial cable. The output power level was set to 10 dBm. The reflections of the antennas were measured from 800 to 1000 MHz. The resonant frequency could be read as a significant drop in the reflection coefficient reading like in Figure 21. The values on the vertical axis of the measurement were the power ratios in decibels and the values on the horizontal axis were the frequencies in MHz.

In the power ratio, the power of the reflected signal is divided by the incident power, and the ratio is converted to decibels with Equation (12).

$$\text{Reflection (dB)} = 10 \log\left(\frac{P_{refl}}{P_{inc}}\right) \quad (12)$$

The resonant frequency of the first antenna was 846 MHz. The result was approximately 3 % off the target frequency of 869 MHz, and therefore the design was modified. The next version of the same antenna was made 5 % shorter lengthwise. The other dimensions were kept the same as in the first version, but the length was decreased to 79.8 mm. Decreasing the length of the patch decreased the resonant wavelength (λ_0) of the antenna, resulting in increased resonant frequency (f_0) according to Equation (13), where c is the speed of light.

$$f_0 = \frac{c}{\lambda_0} \quad (13)$$

The second version of the rectangular antenna had a resonant frequency of 894 MHz which was approximately 3 % too high when compared to the target frequency. From the two data points of the first and second antenna versions, a linear trendline was constructed. According to the linear equation calculated for the trendline and shown in Figure 15, a microstrip antenna with a resonant frequency of 869 MHz corresponded to a patch length of 82.03 mm.

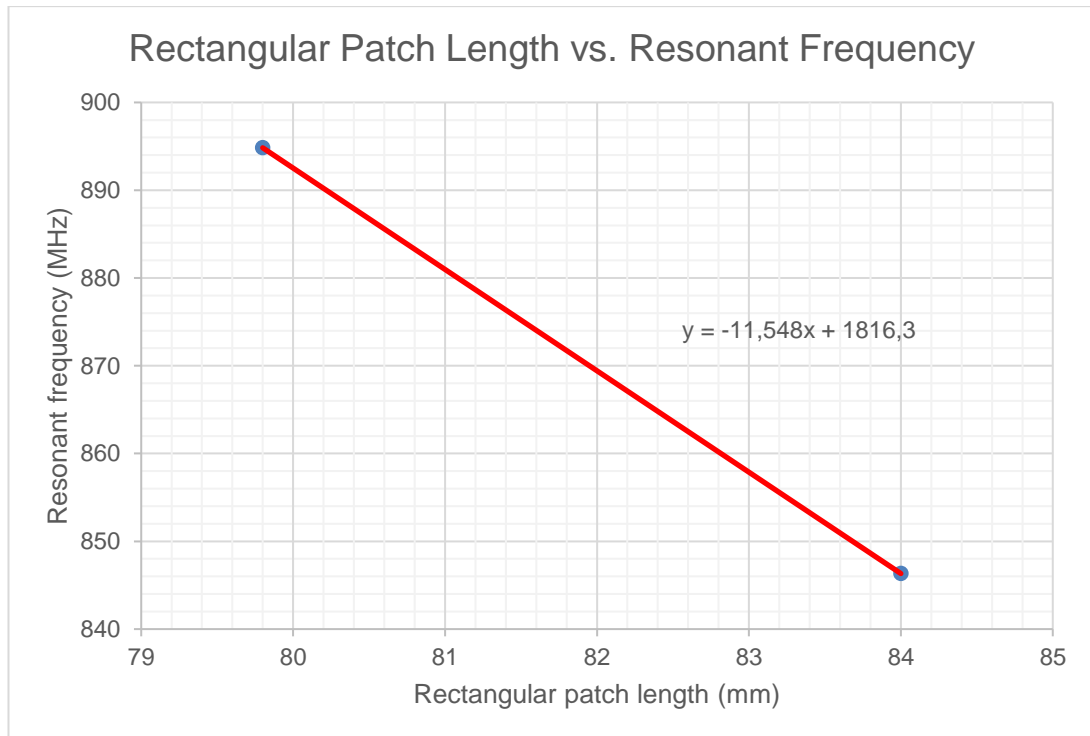


Figure 15. Trendline describing the relationship between patch length and resonant frequency according to the data from the first and second versions of the standard microstrip antenna.

The third version of the standard rectangular microstrip antenna again had the same dimensions as the first version, but the length of the patch was reduced to 82.03 mm. The measured resonant frequency of the third version antenna was 869.9 MHz, which was deemed to be close enough to the target frequency.

Table 3. Rectangular Patch Antenna Sizes.

Rectangular Patch Antenna	Length (L_A) of the antenna patch (mm)	Width (W_A) of the antenna patch (mm)
Version 1	84.05	107.05
Version 2	79.84	
Version 3	82.03	

After adjusting the length of the patch antenna to produce the required resonant frequency, the matching between the antenna and the microstrip line was improved to produce a more lossless signal transmission.

7.1.3 Quarter-Wave Transformer Matching

A quarter-wave impedance transformer was added between the antenna patch and the 50- Ω -microstrip-line of the first version patch antenna to improve matching. The quarter-wave transformer had a length of one quarter of the signal wavelength. The input impedance of the transformer was calculated with Equation (4) to be 60.4 Ω . A microstrip line with input impedance of 60.4 Ω corresponded to a microstrip line with width (W_L) 2.14 mm and length (L_L) 48.8 mm.

Adding the transformer did not influence the resonant frequency of the antenna; it only affected the input impedance as shown in Table 5. The match worsened from the original antenna, which can be seen from the increased reflection coefficient and VSWR values.

7.1.4 Lumped Element Matching

A lumped element circuit was fitted to the midpoint of the antenna's feeding line shown in Figure 16. The impedance of the midpoint was estimated with a VNA by increasing the electrical delay of the impedance reading on the Smith chart until the impedance point was located on the real line of the chart. This point corresponded to the patch impedance. The recorded delay was divided by two, and the impedance of the midpoint was read at that delay point. The impedance locations are shown in Figure 17, where the green point is the system impedance, the red the midpoint impedance, and the blue the patch impedance.

As only the reactance of the halfway delay point needed to be adjusted, a serial inductor was introduced to the feedline midpoint to drive the impedance to the real line. The reactance at the midpoint was -j43.3 Ω . The inductance value for matching was estimated with Equation (14) as 7.8 nH.

$$L = \frac{Z_{ind}}{2\pi f} \quad (14)$$

The copper was stripped from the midpoint, and a 7.5 nH inductor was soldered to the midpoint in series with the feedline. The measured impedance was approximately 79Ω and almost completely real as shown in Table 5. The matching improved signal delivery to the antenna as reflections decreased. The resonant frequency moved to 866 MHz, but the reflection reading was acceptable at 869 MHz at -10.5 dB. Also, the VSWR was below 2 at 1.88.

The lumped element matching of the other antennas was executed in the same fashion and the calculated inductances for the applied components were assembled to Table 6.

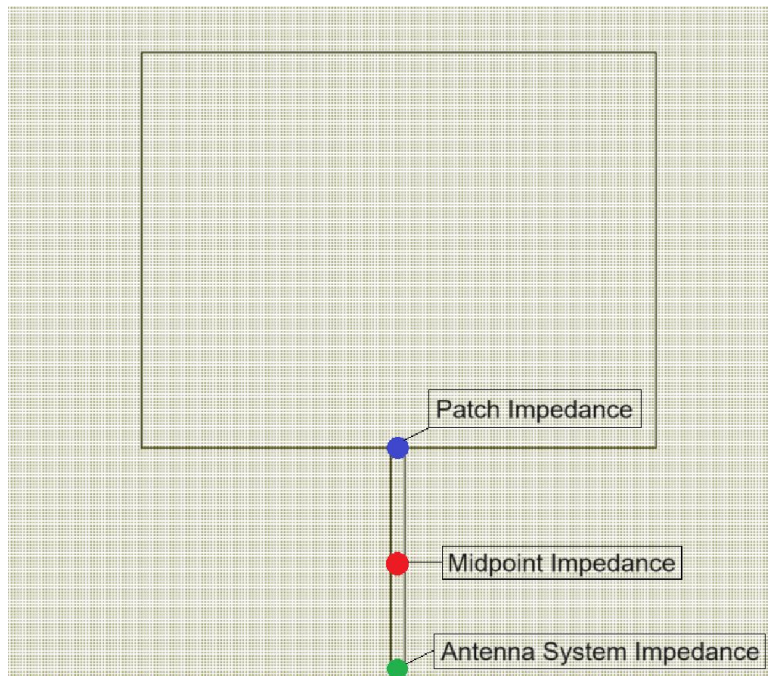


Figure 16. Impedance points illustrated on the patch antenna. The blue point corresponds to the patch impedance point, red point to feedline's midpoint impedance and green point to the antenna input impedance.

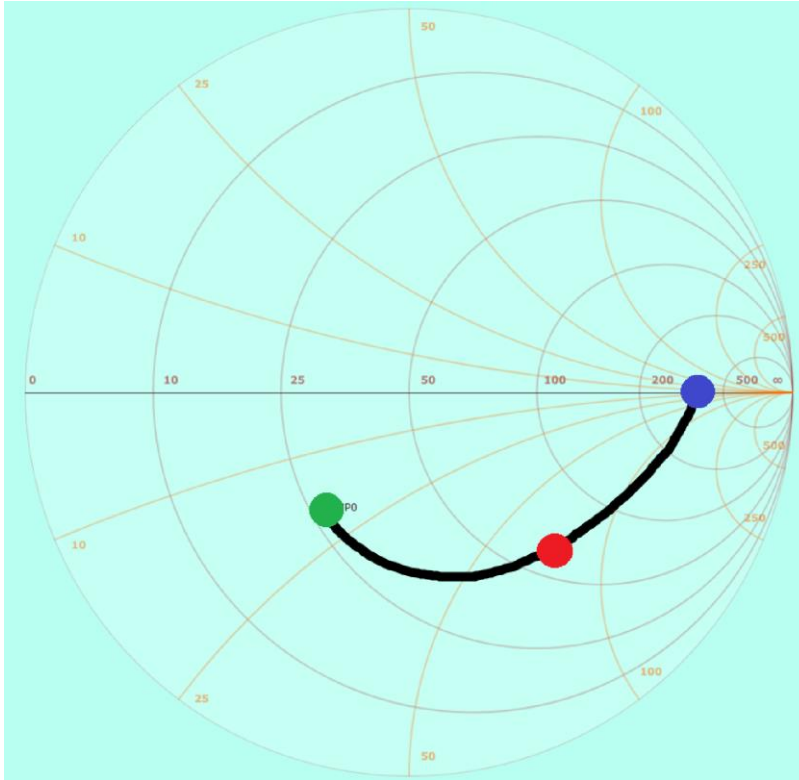


Figure 17. Impedance points corresponding to Figure 16 on a Smith chart. The example values are from the third version rectangular patch antenna.

7.2 Shorted Patch Antenna

The designed shorted patch antennas were fabricated in the same manner as the rectangular patch antennas with the addition of shorting pins. The fabricated antennas were tested, and some also matched with lumped elements.

7.2.1 Fabrication

Fabrication of the shorted patch antennas involved halving the length and width of the original antenna and adding a dense row of shorting pins to the top edge of the antenna, as shown in Figure 18. These shorting pins were soldered to the ground plane, allowing for a significant decrease in the antenna patch size while maintaining the same resonant frequency as the original patch size. Additionally, one of the antennas was shorted using electrical tape instead of shorting pins. The tape connected the outer edge of the antenna to the ground without extending the patch size.

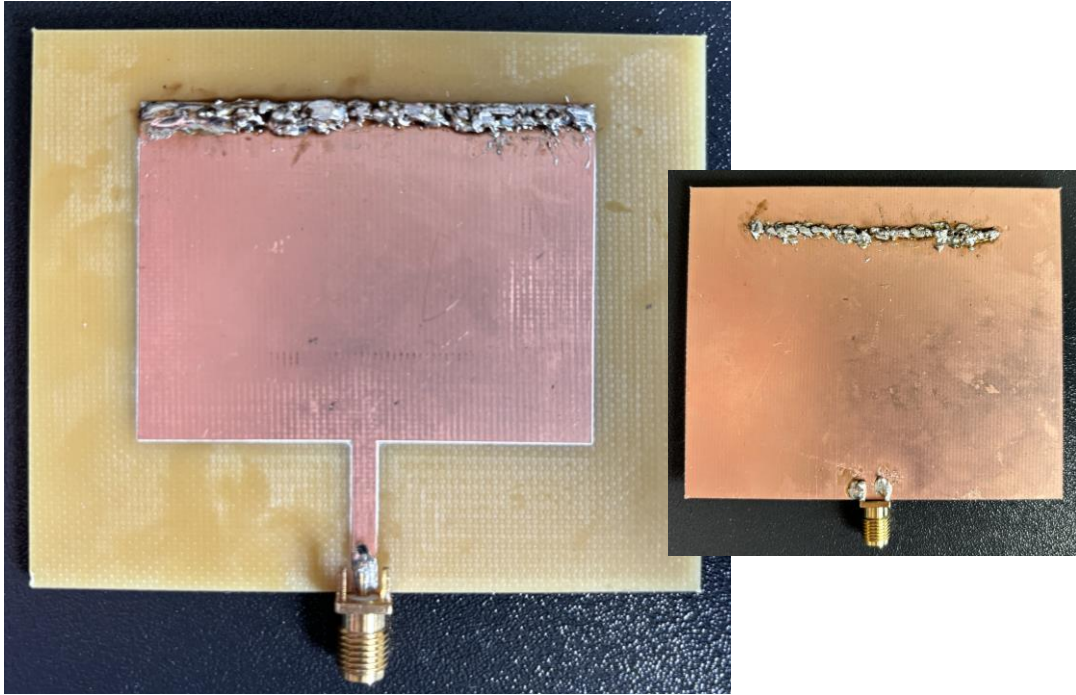


Figure 18. Shorted microstrip antenna with a quarter of the size of the antenna in Figure 14. The left picture is of the topside and the right of the bottom side of the antenna.

Creating five versions of the shorted antenna allowed for experimentation with different patch sizes to determine the optimal dimensions, while maintaining the desired resonant frequency. The first version was precisely a quarter of the size of the first version of the standard microstrip antenna. Subsequent versions had patch lengths close to that of the first shorted version, as detailed in Table 4. This iterative approach enabled refinement of the antenna design to achieve the desired performance characteristics.

7.2.2 Testing

Testing the shorted antennas followed the same procedure as for the rectangular patch antennas. The results of the tests are summarized in Table 5, providing insights into the performance of each shorted antenna variant.

Table 4. Shorted Patch Antenna size chart.

Shorted antenna	Length (L_A) of the patch (mm)	Width (W_A) of the patch (mm)	Shorting Method
Version 1	43.50	53.52	Shorting pins
Version 2	39.92		Shorting pins
Version 3	41.82		Shorting pins
Version 4	41.47		Shorting pins
Version 5	~40		Electrical tape

Determining the length of the antenna patch for the fourth shorted version involved analysing the resonant frequencies of the first three variants and fitting a polynomial curve to these data points. The resulting equation (see Figure 19) was then used to calculate the patch length for the fourth variant. With a measured resonant frequency of 876 MHz, this version was the closest to the target frequency among all the unmatched shorted antennas.

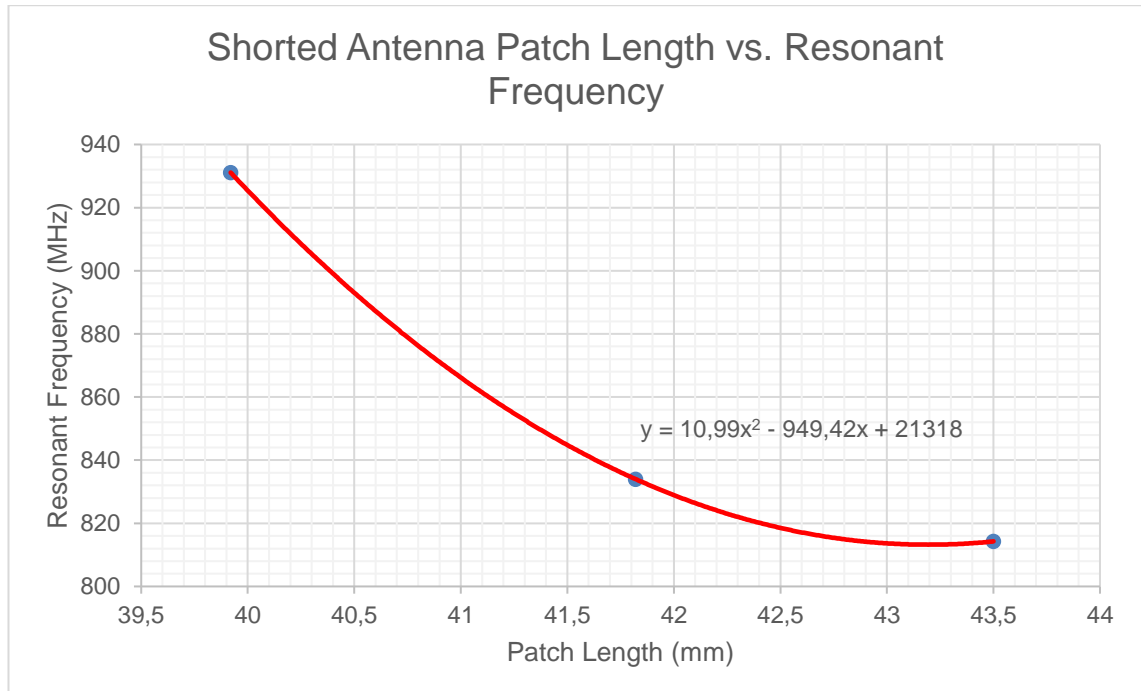


Figure 19. A graph showing the relation between shorted antenna patch length and the measured resonant frequency.

7.2.3 Lumped Element Matching

The resonance frequency of the first shorted antenna was off the target, measuring only 814 MHz. This discrepancy indicated poor matching between the source and the load. To address this, a lumped element circuit was introduced to the midpoint of the feedline, consisting of a single 12 nH inductor. This adjustment notably improved antenna performance, as evidenced in Table 5.

The second version of the shorted antenna, being 5% shorter in length than the first, resulted in a resonant frequency of 931.1 MHz. Given that this frequency was significantly higher than the target frequency, no further matching adjustments were completed, as they were unlikely to substantially affect the resonant frequency.

The third and fourth versions of the shorted antennas were also matched with inductors, as detailed in Table 6. These matching adjustments similarly led to significant improvements, with notable decreases in VSWR and reflection coefficient values.

7.3 Result Comparison

The impedance measurements of all the antennas were collected into Table 5. The rectangular patch antennas were close to specifications without matching. The shorted antennas were out of specifications to begin with, but matching improved their performance substantially.

Out of all the fabricated antennas, the third version rectangular patch antenna with lumped element matching resulted in the best resonant frequency. In addition, the performance of the antenna was undoubtedly within specifications. The third version had a resonant frequency of 866 MHz, but its bandwidth covered the critical frequency of 869 MHz, since the VSWR at that point was 1.88 and the reflection coefficient -10.5 dB.

The top-performing shorted antenna was the fourth version which had a great resonant frequency before matching. The matching improved its performance, but also modified the resonant frequency resulting in an antenna, which was not within specifications at the target frequency of 869 MHz.

Table 5. VNA measurements of the antennas.

Antenna	Resonant frequency f_0 (MHz)	Input impedance		Reflection at f_0 (dB)	VSWR
		Resistance (Ω)	Reactance ($j\Omega$)		
Rectangular Patch v1	846.4	37.6	-9.5	-14.5	1.4
Rectangular Patch v2	896.3	27.5	-11.7	-9.8	1.9
Rectangular Patch v3	869.9	27.1	-19	-9.5	2.1
Rectangular Patch v1 Matched with Quarter-wave Transformer	846.4	51	28	-11.3	1.7
Rectangular Patch v3 Matched with Lumped Element	866.1	79.0	-1.57	-13.2	1.6
Shorted v1	814.3	64.7	-73	-5.3	5.2
Shorted v2	931.1	12.4	-36.7	-2.7	6.3
Shorted v3	835.2	60	-93	-3.6	4.7
Shorted v4	876.0	14.7	-36.2	-3.3	5.3
Shorted v5	925.4	33.5	-17.7	-13.5	1.8
Matched Shorted v1	846.0	29.2	-2.9	-11.5	1.7

Antenna	Resonant frequency f_0 (MHz)	Input impedance		Reflection at f_0 (dB)	VSWR
		Resistance (Ω)	Reactance ($j\Omega$)		
Matched Shorted v3	834.4	43.3	-1.73	-21.9	1.2
Matched Shorted v4	847.2	44.1	6.83	-20.3	1.2

Table 6. Antenna matching specifications.

Antenna	Matching Technique	Component	Improved Matching
Rectangular Patch version 1	Quarter-wave transformer	Microstrip line with $\frac{\lambda}{4}$ length	No
Rectangular Patch version 3	Lumped element	7.5 nH inductor	Yes
Shorted version 1	Lumped element	12 nH inductor	Yes
Shorted version 3	Lumped element	15 nH inductor	Yes
Shorted version 4	Lumped element	7.5 nH inductor	Yes

8 Simulation

Simulation of microstrip antennas requires software capability in 3D electromagnetic simulation. CST (Computer Simulation Technology) Studio Suite, ANSYS HFSS (High-Frequency Structure Simulator) and AWR (Applied Wave Research) Axiem Analysis are examples of such software. In this thesis AWR Axiem Analysis was utilised in antenna performance simulations.

8.1 AWR AXIEM Analysis

Cadence's AWR AXIEM Analysis is a three-dimensional simulator for electromagnetic structures such as sizable planar antennas and transmission lines. The software applies Method of Moments (MoM) analysis in its return loss,

radiation pattern, VSWR and other related antenna measurement simulations. [14.] The Method of Moments is a numerical technique used in transforming linear functional equations that describe electromagnetic behaviour to solvable linear matrix equations. [15.]

8.2 Rectangular Patch Antenna Simulation

Firstly, a three-dimensional version of the patch antenna was constructed in AWR. The structure is shown in Figure 20 where the patch and the ground plane are separated by FR-4 substrate with a thickness of 1.5 mm and a dielectric constant of 4.2. Number 1 in the figure points to the location of the signal input port.

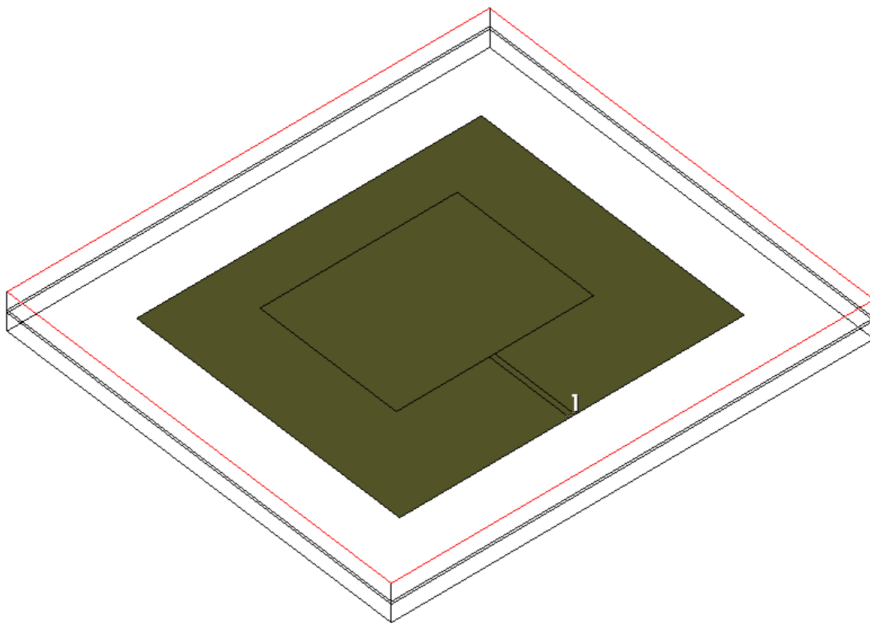


Figure 20. Three-dimensional simulation of a rectangular patch antenna in AWR.

After the structure was finished, the VSWR, S_{11} and radiation patterns were simulated. This process was repeated for all the fabricated rectangular patches and the results were collected to Table 7. As the simulated graphs were alike, only the first version patch antenna graphs were presented as examples of all the rectangular patch antennas.

Figure 21 presents the S-parameter graph of the antenna input or S_{11} between 840 and 900 MHz for the first version rectangular patch antenna. The dimensions of the antenna are defined in Table 3. There is a clear drop in the reflection coefficient reading at 873 MHz indicating that the resonant frequency is located at that point. Similarly, Figure 22 shows the behaviour of VSWR in the same frequency range, again reaching its lowest value at 873 MHz.

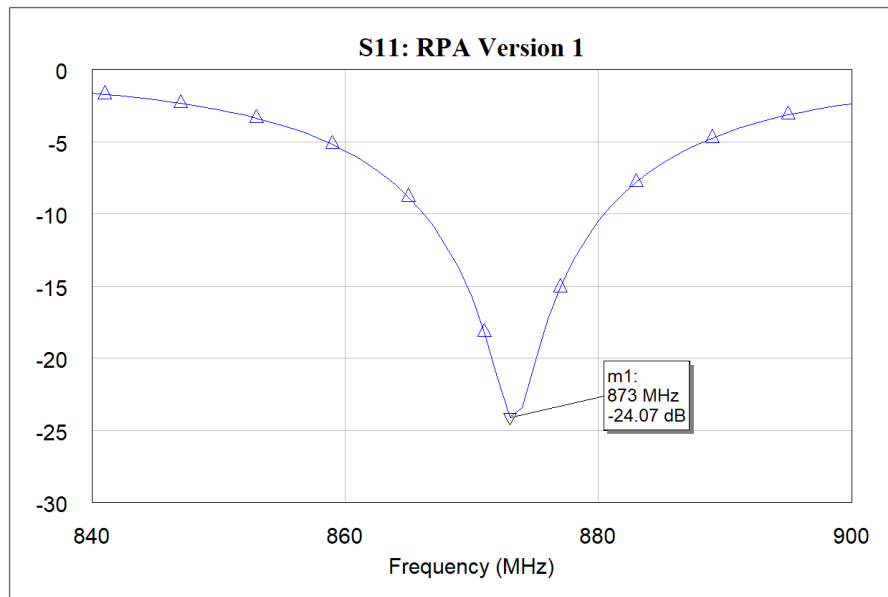


Figure 21. The S_{11} measurement of the first version rectangular patch antenna. The marker m1 points out the resonant frequency and the corresponding reflection coefficient in dB.

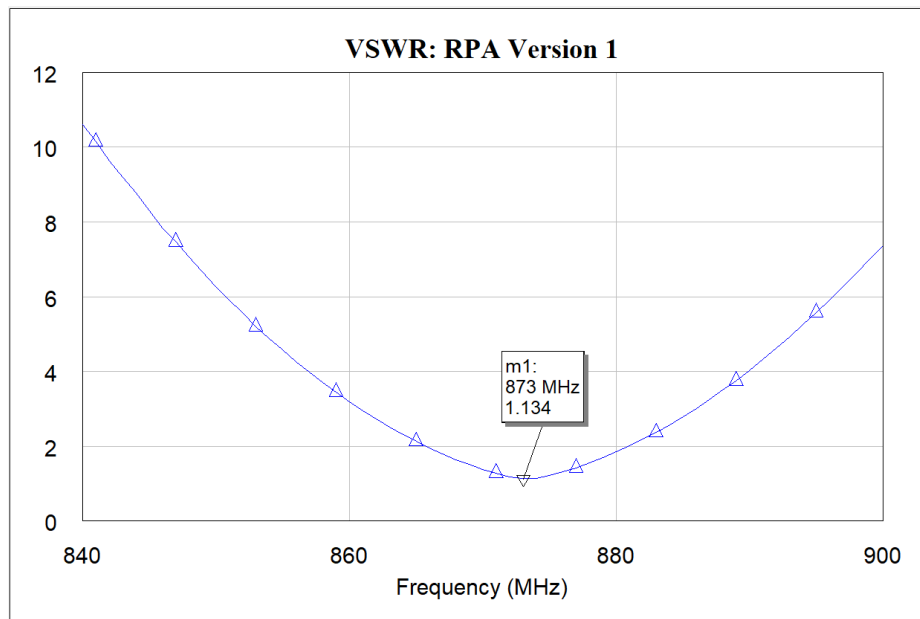


Figure 22. VSWR measurement of the first rectangular patch antenna. The marker m1 points out the lowest VSWR value and the corresponding frequency.

The input impedance of the antenna at frequency 873 MHz is close to the optimal 50Ω point on the Smith chart as shown in Figure 23, implying that the matching attributes of VSWR and reflection coefficient should be within specifications. According to Table 7 they very well are with $-24 \text{ dB} < -10 \text{ dB}$ and $1.13 \leq 2$. Equivalently, the impedances of the second, third, and quarter-wave transformer versions were within specifications. Only the lumped element matching resulted in a poor impedance match and performance outside specifications.

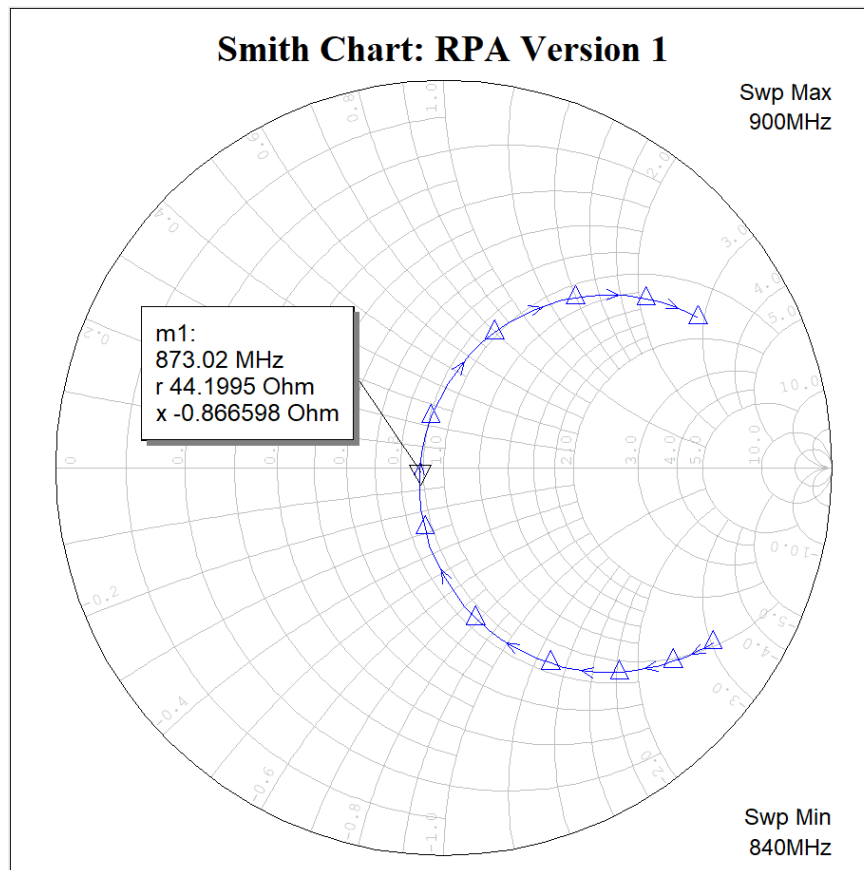


Figure 23. Input impedance measurements of the first version rectangular patch antenna on a Smith chart. The marker m1 is located at the measurement point corresponding to the resonant frequency of 873 MHz.

The radiation pattern simulation of the first antenna is shown in Figure 24 and the directivity diagram in Figure 25. The radiation pattern is displayed in polar coordinates, and the numbers on the graph circumference indicate the angle, i.e., the direction of radiation. The radius of the graph represents the magnitude of radiation in that direction. Here, the radiation pattern and the directivity are given at the frequency of 870 MHz. Each gridline represents a 10 dB change in magnitude. The radiation is at maximum perpendicularly to the patch.

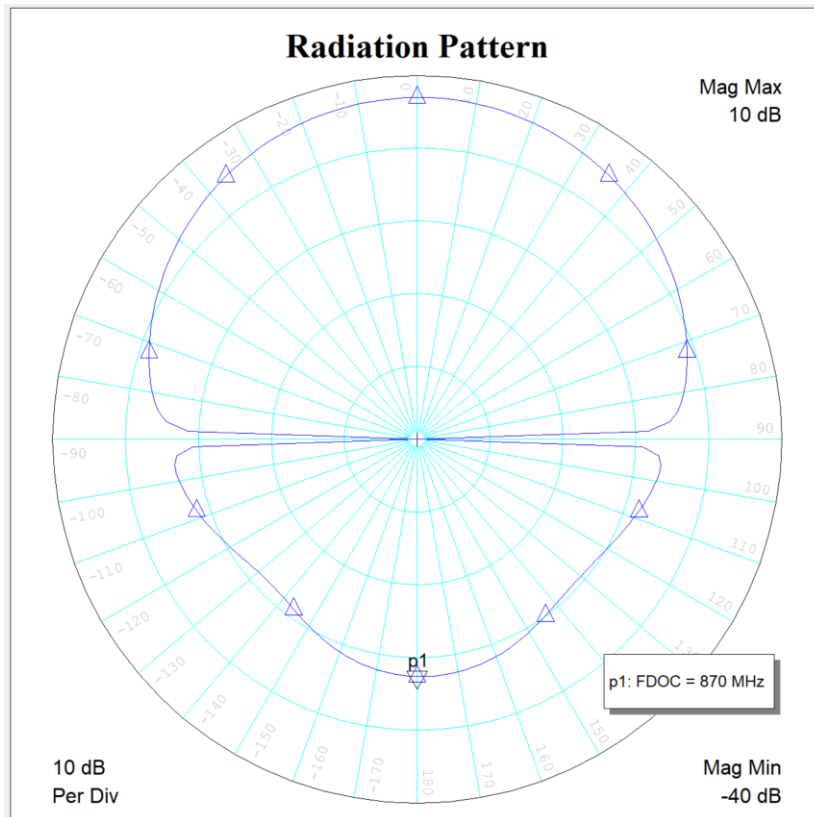


Figure 24. Two-dimensional radiation pattern of the first rectangular patch antenna. The marker p1 indicated the radiation pattern measurement frequency which was set to 870 MHz.

The 3D graph presents the directivity of the simulated antenna. The antenna is located between the two separate directivity areas. Directivity is the measure of the concentration of radiated power in a particular direction when compared to an isotropic radiator. A directivity of 1 corresponds to an isotropic radiator, and anything above that indicates stronger radiation in said direction. In Figure 25, the antenna focuses most of its radiated power above the patch, whereas below the patch the radiation is weaker than in an isotropic antenna.

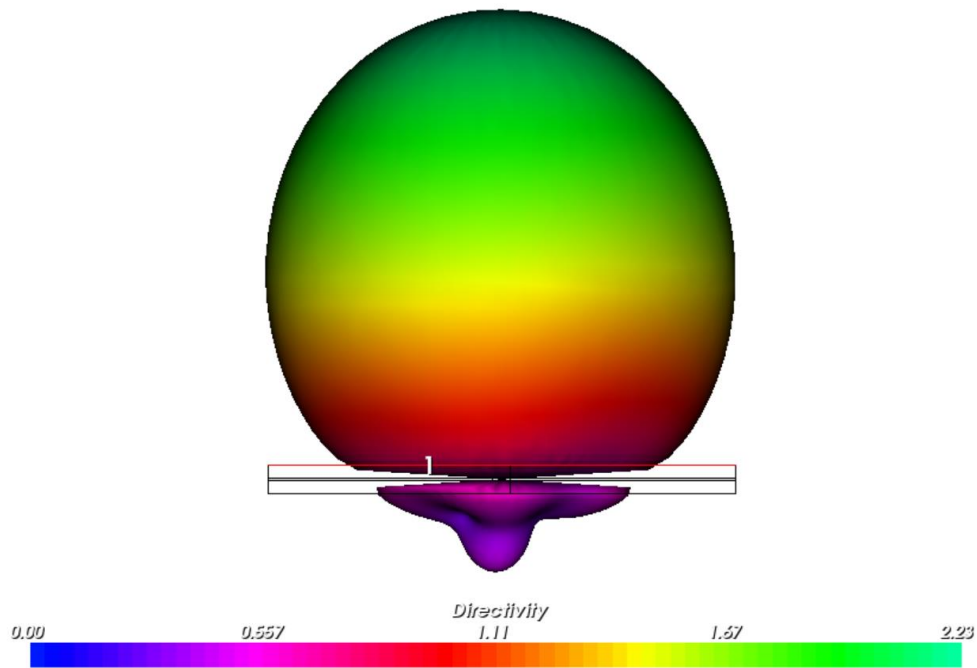


Figure 25. Three-dimensional directivity graph of the first version rectangular patch antenna.

The lumped element matching was simulated by adding two new ports to the antenna EM structure, and then placing the antenna design as a subcircuit to a schematic. The schematic is illustrated by Figure 26. An inductor was placed between ports 2 and 3 in the middle of the microstrip feeding line. Port 1 was kept as the input port to the antenna system.

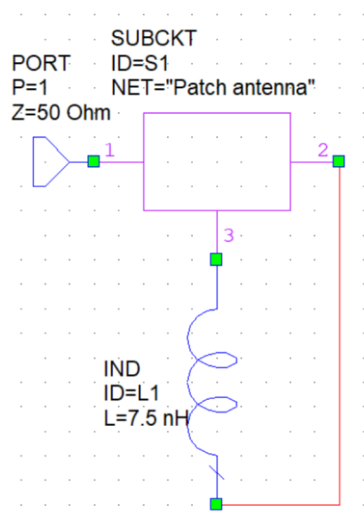


Figure 26. AWR simulation schematic for lumped element matching.

Table 7. Rectangular patch antenna simulation results for resonant frequency, input impedance, VSWR, S_{11} and bandwidth.

Rectangular Patch Antenna	Resonant frequency (MHz)	Input impedance (Ω)	VSWR	S_{11} (dB)	Bandwidth (MHz) $VSWR \leq 2$
Version 1	873	$44.2 - j0.87$	1.13	-24.1	866-881
Version 2	918	$43.7 + j0.67$	1.18	-23.8	910-926
Version 3	894	$44.4 + j0.74$	1.14	-24.1	886-902
Version 1 with Quarter-Wave Transformer	873	$44.5 + j0.14$	1.23	-19.8	867-880
Version 3 with Lumped Element Matching	892	$46.7 - j173$	2.04	-9.33	-

8.3 Shorted Rectangular Antenna

Shorted antennas were simulated in a similar manner to the rectangular patch antennas. The main difference in the antenna layout was the smaller size of the patch and the addition of shorting pins to the outermost edge of the antenna. The shorted antenna layout is demonstrated in Figure 27.

The changes in the layout affected the performance of the antenna. The simulated measurements produced visually similar graphs and illustrations, which is why the examples in this chapter represent every shorted antenna simulation. All numerical results are collected to Table 8.

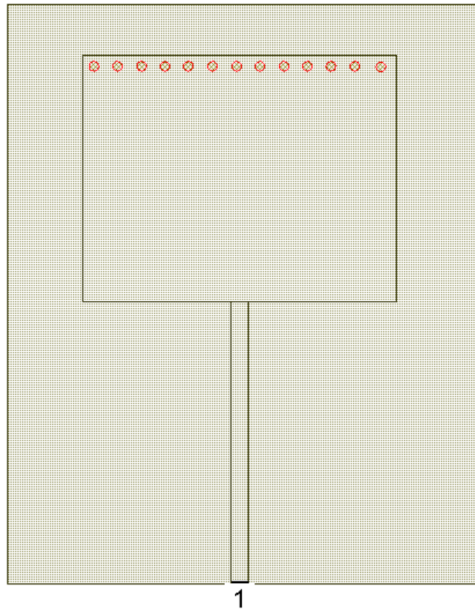


Figure 27. Two-dimensional shorted antenna layout in AWR.

The S_{11} curve of the first version shorted antenna in Figure 28 is relatively shallow when compared to Figure 21, which shows the corresponding curve for a rectangular patch antenna. The reflection coefficient of -3.94 dB was almost five times higher than in the rectangular patch simulation. Furthermore, the VSWR is 4.5 at its lowest point as shown in Figure 29. This value is almost twice the commonly agreed upper limit of VSWR at 2 indicating that the antenna is not as efficient as expected. The simulated shorted antenna results in Table 8 show very similar behaviour with the first version design. The bandwidths of the nonmatched antennas were omitted from the table as they were not within specifications.

Matching the shorted antennas with a lumped element improved the performance characteristics of the antennas which can be observed from the results in Table 8.

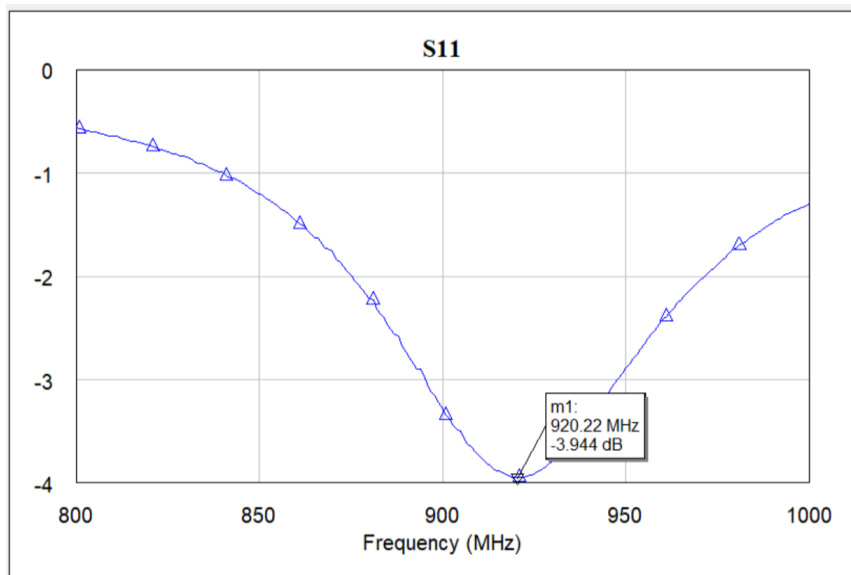


Figure 28. Reflection coefficient measurement of the first version shorted antenna.

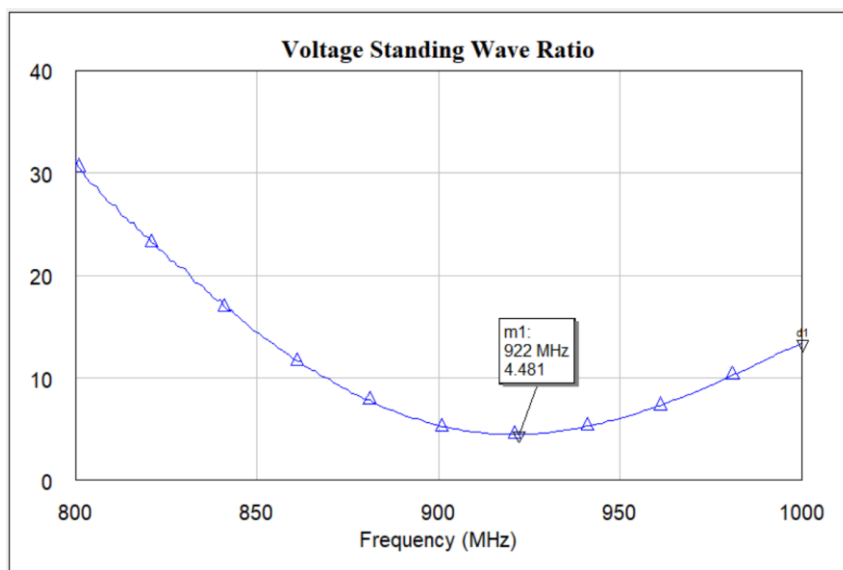


Figure 29. VSWR measurement of the first version shorted antenna.

The radiation pattern of the shorted antenna design is seen in Figure 30 and directivity in Figure 31. The shorted antenna had a more widely distributed radiation area than the rectangular patch antenna. The maximum power was mostly directed outwards perpendicularly to the patch where the radiation was at comparable levels to an isotropic antenna. Likewise, a significant portion of the radiation was directed perpendicularly outwards from the ground plane of the antenna.

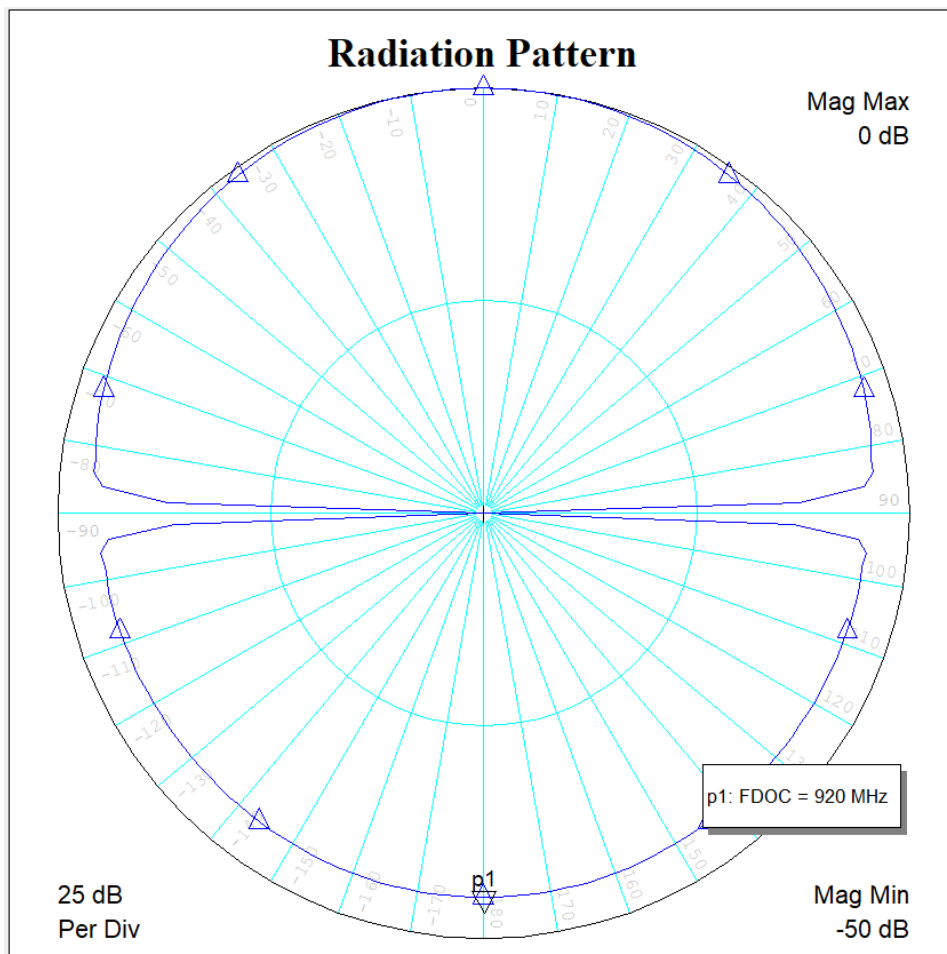


Figure 30. Radiation pattern of the first version shorted antenna.

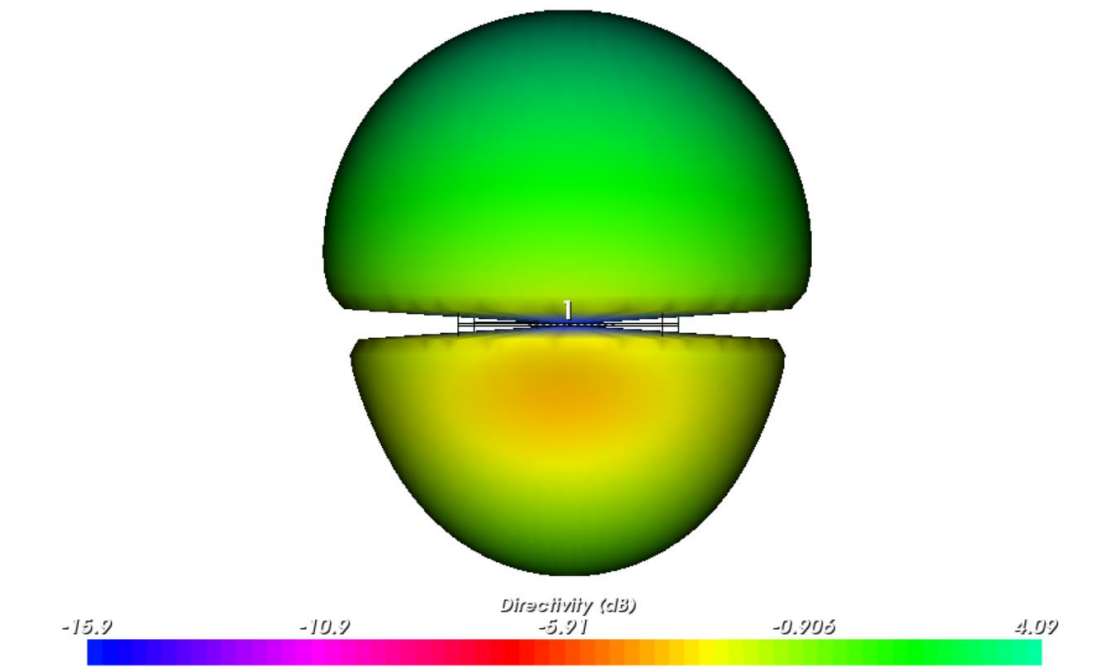


Figure 31. Three-dimensional directivity graph of the first version shorted antenna.

Matching a shorted antenna with a lumped element added a dent to the outer radiating edge where the radiating power was distinctly less than in an isotropic radiator. The dent in directivity is depicted in Figure 32.

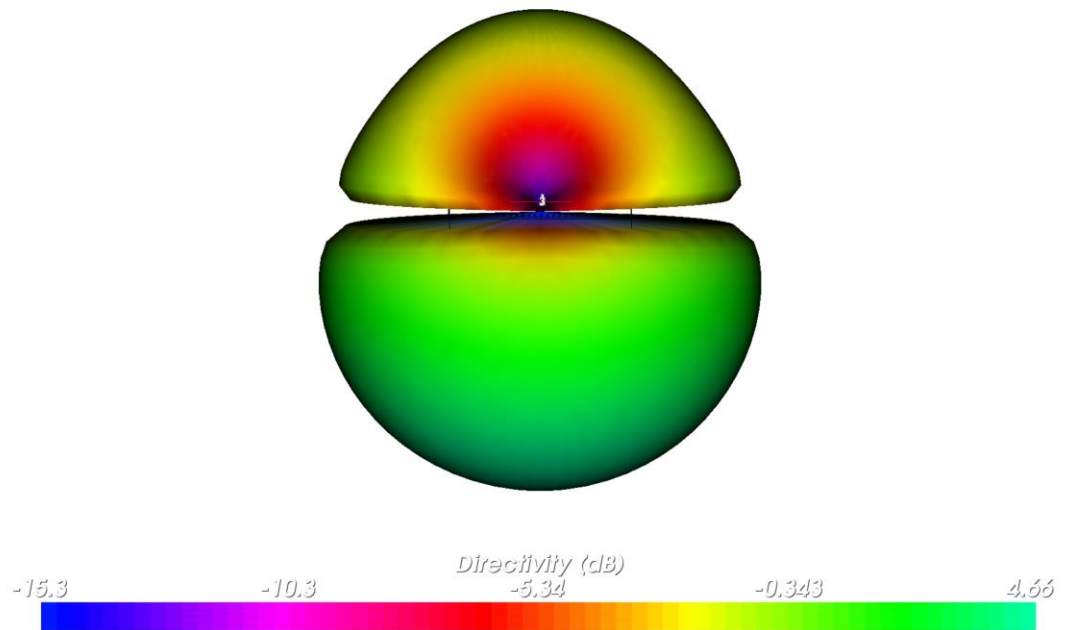


Figure 32. The directivity graph of a shorted and matched antenna.

Table 8. Simulated performance results for shorted antennas.

Shorted Antenna	Resonant frequency (MHz)	Input impedance (Ω)	VSWR	S_{11} (dB)	Bandwidth (MHz) VSWR ≤ 2
Version 1	922	$11.3 + j5.51$	4.48	-3.94	-
Version 2	973	$11.9 + j10.3$	4.41	-4.01	-
Version 3	925	$11.5 + j5.35$	4.47	-3.95	-
Version 4	934	$11.5 + j7.19$	4.47	-3.96	-
Version 5	974	$12.1 + j13.4$	4.45	-3.97	-
Version 1 with Lumped Element Matching	906	$40.3 + j11.4$	1.39	-15.7	888-912
Version 3 with Lumped Element Matching	908	$43.9 + j1.70$	1.15	-23.6	901-915
Version 4 with Lumped Element Matching	924	$26.6 + j8.06$	1.95	-9.86	923-926

8.4 Comparison of Physical and Simulated Results

A clear trend existed where the rectangular patch antennas produced better performance-related results when compared to the shorted antennas both in physical measurements and simulations. Furthermore, the results noticeably differed between the actual and simulated measurements for the two antenna types and all their impedance matched versions.

9 Future Directions and Conclusions

This thesis was a study of the properties of rectangular microstrip antennas. The practical work involved design, fabrication, testing and simulation of microstrip antennas. The resonance frequencies, input impedances, reflection coefficients, and bandwidths of the fabricated antennas were tested to evaluate their performance, and the results were analysed.

Performance enhancement of the fabricated rectangular and shorted patch antennas was studied with quarter-wave transformer and lumped element impedance matching techniques. Of these two methods, the single-component lumped element matching produced better outcomes and evidently improved the performance of the antennas.

9.1 Challenges and Opportunities

Some challenges and several opportunities were encountered during this thesis work. The antennas were not tested as thoroughly as industrially manufactured antennas typically are. The lack of testing was to do with the teaching application for which the antennas were designed. Intense testing was unnecessary since the resonant frequency was the primary focus when estimating the accomplishments of the project.

Approaching the project through a practical mindset by firstly fabricating the antennas and testing them before simulations was fruitful, because the results

between authentic antennas and simulated antennas differed substantially. The simulations could not have been reliably used to design antennas with the required specifications.

9.2 Recommendations for Future Work

In future work the performance of the manufactured antennas could be more closely investigated. Especially gain, efficiency and polarisation measurements would give valuable information about the operation of the studied antennas.

The complexity of the antenna design could be increased to enhance some of the restricting qualities of the fabricated microstrip antennas such as the narrow bandwidth and large surface area. These could be achieved by changing the substrate to a material with a higher dielectric constant such as ceramics.

The study of miniature microstrip antennas is of particular interest due to the high demand of increasingly smaller antennas. These antennas need work up to the high standards which are expected from current antennas. Additionally, the bandwidth of microstrip antennas is predicted to expand to accommodate for varied signal frequencies in communication technology.

Improving the simulations to correspond even better with the fabricated antennas would be a useful approach to advancing the thesis work. Eventually, the simulations could be used to accurately predict the behaviour of the antennas without the need for fabrication and testing.

9.3 Summary and Concluding Remarks

The basic principles explaining the behaviour of microstrip antennas were studied. Their implementation in the design, simulation and testing of microstrip antennas was considered and the results analysed.

The intention of the work was to create a microstrip antenna with a resonant frequency of 869 MHz. An antenna with a resonant frequency of 866 MHz was constructed, and its bandwidth covered the critical point of 869 MHz. In addition, antennas with varying resonant frequencies on the ISM band were created and they all can be utilised in teaching depending on the needs of the teacher and the course.

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Formulas for Microstrip Antenna Design

The formulas for calculating the physical dimensions of a patch antenna are derived from transmission line and resonance condition equations. Figure 1 illustrates the patch antenna dimensions and their symbols.

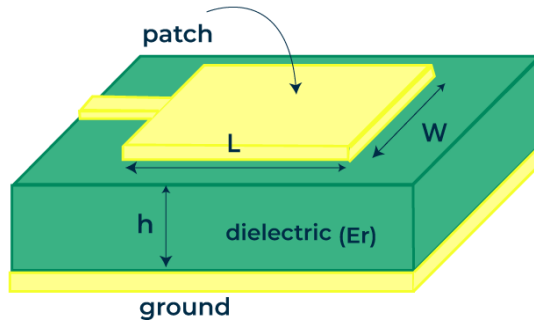


Figure 1. Dimensions of a microstrip patch antenna [16].

The width (W_A) of the antenna patch is calculated with Equation (1).

$$\text{Width } (W_A) = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

Here c is the speed of light and ϵ_r is the permittivity of the substrate material. The effective permittivity of a transmission line (ϵ_{eff}) determines the behaviour of signal propagation and it is calculated with Equation (2).

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12 \left(\frac{h}{W_A} \right)}} \right] \quad (2)$$

In Equation (2) h denotes the thickness of the substrate material. Finally, the length (L_A) of the patch is calculated with Equation (3).

$$\text{Length } (L_A) = \frac{c}{2f_0 \sqrt{\epsilon_{eff}}} - 0.824h \left(\frac{(\epsilon_{eff} + 0.3) \left(\frac{W_A}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W_A}{h} + 0.8 \right)} \right) \quad (3)$$

Formulas for Microstrip Line Design

The effective width (W_L) and length (L_L) of a microstrip line can be calculated with Equations (4) and (5).

$$W_L = w + \frac{t}{\pi} \left[\ln \left(\frac{2h}{t} \right) + 1 \right] \quad (4)$$

$$L_L = h - 2t \quad (5)$$

In Equations (4) and (5) w is the width and t the thickness of the trace, and h is the thickness of the substrate. The formulas used for calculating the input impedance of the microstrip line depend on the ratio between the width and height of the microstrip line.

When $\frac{W_L}{H_L} < 1$, Equations (6) and (7) are utilised.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[\frac{1}{\sqrt{1 + 12 \frac{H}{W}}} + 0.04 \left(1 - \frac{W_L}{L_L} \right)^2 \right] \quad (6)$$

$$Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} \ln \left(\frac{8H_L}{W_L} + \frac{W_L}{4L_L} \right) \Omega \quad (7)$$

When $\frac{W_L}{L_L} \geq 1$, Equations (8) and (9) are applied.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{\sqrt{1 + 12 \frac{L_L}{W_L}}} \quad (8)$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff} \left[\frac{W_L}{L_L} + 1.393 + \frac{2}{3} \ln \left(\frac{W_L}{L_L} + 1.444 \right) \right]}} \Omega \quad (9)$$

Maxwell's Equations

According to Gauss's Law in Equation (10), an electric field is created by charged particles.

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{in}}{\epsilon_0} \quad (10)$$

A changing magnetic field creates an electric field as described by Faraday's Law in Equation (11).

$$\oint \vec{E} \cdot d\vec{s} = -\frac{d\Phi_m}{dt} \quad (11)$$

Magnetic monopoles do not exist according to Gauss's Law for Magnetism in Equation (12).

$$\oint \vec{B} \cdot d\vec{A} = 0 \quad (12)$$

Ampère-Maxwell Law describes currents and a changing electric field creating a magnetic field in Equation (13). [2,1096.]

$$\oint \vec{B} \cdot d\vec{s} = \mu_0 I_{through} + \epsilon_0 \mu_0 \frac{d\Phi_e}{dt} \quad (13)$$

Lorentz Force Law

In the Lorentz Force Law, a charged particle in an electric field is the target of an electric force and similarly a charge moving in a magnetic field experiences a magnetic force. Lorentz Force Law is described by Equation (14). [2,1097.]

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (14)$$