



A NOVEL TRIPLE-BAND MICROSTRIP ANTENNA

Elif SAFEL

SEPTEMBER 2024

ÇANKAYA UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

M.Sc. Thesis in

ELECTRICAL AND ELECTRONICS ENGINEERING



A NOVEL TRIPLE-BAND MICROSTRIP ANTENNA

Elif SAFEL

SEPTEMBER 2024

ABSTRACT

A NOVEL TRIPLE-BAND MICROSTRIP ANTENNA

SAFEL, ELİF

M.Sc. in Electrical and Electronics Engineering

Supervisor: Assoc. Prof. Dr. Göker Şener

September 2024, 86 pages

This thesis covers a novel single-layer triband microstrip antenna designed and developed for the needs of communication systems. This designed antenna has been proven to perform at 1.55 GHz, 2.00 GHz and 1.95 GHz resonant frequencies through simulation and experimental investigations. The designed antenna has become suitable for use in applications such as 4G, 5G, Wi-Fi and satellite communications at these frequencies.

The theoretical design is based on the resonance of the three different rectangular patches that are present in the overall patch geometry with low backscattering ratios. This triband microstrip antenna has the capacity to operate at three different frequencies simultaneously, saving space and cost by supporting signal flow with multiple devices. This designed antenna expands the usage areas and helps to reduce the size of the devices and prevent system complexity by creating lighter structures. Triband capability provides performance improvements such as extended coverage and improved signal reliability. It is a suitable choice for applications operating under harsh environmental conditions or at varying frequencies due to different network structures.

Keywords: Antenna Design, Microstrip Antenna, Wireless Communication, Multi-band Systems, RF Engineering.

ÖZET

YENİ ÜÇ BANTLI MİKROŞERİT ANTEN

SAFEL, ELİF

Elektrik-Elektronik Mühendisliği Yüksek Lisans

Danışman: Doç. Dr. Göker Şener

Eylül 2024, 86 sayfa

Bu tez, haberleşme sistemlerinin ihtiyaçları için tasarlanmış ve geliştirilmiş yenilikçi bir tek katmanlı üç bantlı mikroşerit anteni kapsamaktadır. Tasarlanan bu anten, simülasyon ve deneysel araştırmalar ile 1.55 GHz, 2.00 GHz ve 1.95 GHz rezonans frekanslarında başarılı bir performans sergilediği kanıtlanmıştır. Bu frekanslarda, anten 4G, 5G, Wi-Fi ve uydu iletişimi gibi uygulamalar için uygun hale gelmiştir.

Teorik tasarım, düşük geri saçılma oranlarına sahip olan ve genel yama geometrisinde bulunan üç farklı dikdörtgen yamanın rezonansına dayanmaktadır. Bu üç bantlı mikroşerit anten, aynı anda üç farklı frekansta çalışabilme kapasitesine sahiptir. Birden fazla cihazla sinyal akışını destekleyerek yer ve maliyet tasarrufu sağlar. Tasarlanan bu anten, mikroşerit antenlerin kullanım alanlarını genişletir, cihazların boyutunu küçültmeye yardımcı olur ve daha hafif yapılar oluşturarak sistem karmaşıklığını önler. Üç bantlı kapasitesi, genişletilmiş kapsama alanı ve iyileştirilmiş sinyal güvenilirliği gibi performans iyileştirmeleri sunar. Zorlu çevresel koşullarda veya farklı ağ yapıları nedeniyle değişen frekanslarda çalışan uygulamalar için uygun bir seçimdir.

Anahtar Kelimeler: Anten Tasarımı, Mikroşerit Anten, Kablosuz İletişim, Çok Bantlı Sistemler, RF Mühendisliği.

ACKNOWLEDGEMENT

I would like to express my deepest gratitude to my advisor, Assoc. Prof. Dr. Göker Şener, for his guidance and invaluable contributions throughout the preparation of this thesis. He has always supported me by generously sharing his knowledge and experience during my thesis work. Without his direction and patience, it would not have been possible to complete this study.

I would also like to thank my family and friends who supported me throughout this process. Their understanding and encouragement made this journey much easier.

Lastly, I feel indebted to express my thanks to all the faculty members, colleagues, and Çankaya University staff who contributed to this process.

TABLE OF CONTENTS

STAMENT OF NONPLAGIARISM.....	III
ABSTRACT	IV
ÖZET.....	V
ACKNOWLEDGEMENT	VI
LIST OF TABLE.....	IX
LIST OF FIGURES	X
LIST OF SYMBOLS AND ABBREVIATIONS	XII
CHAPTER I.....	1
INTRODUCTION.....	1
1.1 Purpose of the Study	1
1.2 History and Types of Antennas.....	1
1.3 Antenna Parameters	15
CHAPTER II	23
MICROSTRIP ANTENNAS.....	23
2.1 History of Microstrip Antennas	23
2.2 General Concept of Mikrostrip Antennas	24
2.3 Analysis Methods in Microstrip Antennas	35
CHAPTER III.....	43
MULTIPLE BAND MICROSTRIP ANTENNA	43
3.1 Multiband Microstrip Patch Antennas	43
3.2 Dual-Band Microstrip Antennas	43
3.3 Triple-band Microstrip Antennas.....	50
CHAPTER IV.....	54
DESIGN AND ANALYSIS OF A TRIPLEBAND MICRISTRIP ANTENNA..	54
4.1 A Tri-Band Antenna Design Principle.....	54
4.2 Geometry and Configuration of the Microstrip Antenna.....	55
4.3 Parametric Analysis and HFSS Simulation	60
4.4 Impedance Matching and Inset Feeding	66

4.5 Implementation And Experimental Validation.....	66
CHAPTER V	70
REFERENCES.....	71



LIST OF TABLES

Table 1: Geometric Lengths of Microstrip Antenna	55
Table 2: Dimension of Inset Feeding on the Tri-Band Microstrip Antenna	66



LIST OF FIGURES

Figure 1: Normalized three-dimensional amplitude field pattern	17
Figure 2: Basic Concept of a Microstrip Antenna	25
Figure 3: E-plane arrangements of microstrip patch antennas.....	34
Figure 4: H-plane arrangements of microstrip patch antennas	34
Figure 5: Charge distribution and current density creation on microstrip patch	38
Figure 6: Stub and frequency	46
Figure 7: RMSA with two stubs	46
Figure 8: (a)Square MSA with a notch (b)variation of resonance frequencies	47
Figure 9: Dual frequency MSA at the S- and X-bands	49
Figure 10: Dimensions of the Microstrip Antenna	55
Figure 11: Field configurations (modes) for rectangular microstrip patch.....	57
Figure 12: E-Field Analyses at 1.55 GHz on the Antenna Patch.....	58
Figure 13: Corresponding Length of E-Field Analyses at 1.55 GHz (L_1).....	58
Figure 14: E-Field Analyses at 2.00 GHz on the Antenna Patch.....	59
Figure 15: Corresponding Length of E-Field Analyses at 2.00 GHz (L_2).....	59
Figure 16: E-Field Analyses at 2.92 GHz on the Antenna Patch.....	59
Figure 17: Corresponding Length of E-Field Analyses at 2.92 GHz (L_3).....	60
Figure 18: Port Setting Configuration.....	61
Figure 19: Driven Solution Setup	62
Figure 20: S11 Parameter of Tri-Band Microstrip Antenna	63
Figure 21: S11 Parametric Result of bY Lenght.....	63
Figure 22: S11 Parametric Result of dY Lenght	64
Figure 23: Gain Plot of The Tri-Band Microstrip Antenna at 1.55 GHz.....	65
Figure 24: Gain Plot of The Tri-Band Microstrip Antenna at 2.00 GHz.....	65
Figure 25: Gain Plot of The Tri-Band Microstrip Antenna at 2.92 GHz.....	65
Figure 26: Inset Feeding of the Tri-Band Microstrip Antenna	66
Figure 27: Photo of the Triple Band Microstrip Antenna	67
Figure 28: VNA S11 Graph of Tri-Band Microstrip Antenna	68

Figure 29: $ S_{11} $ results of HFSS and VNA	68
Figure 30: Total Power Density at 1.55 GHz.....	69
Figure 31: Total Power Density at 2.00 GHz.....	69
Figure 32: Total Power Density at 2.92 GHz.....	69



LIST OF ABBREVIATIONS

MSA	: Microstrip Antenna
RMSA	: Rectangular Microstrip Antenna
CMSA	: Circular Microstrip Antenna
TMSA	: Triangular Microstrip Antenna
RF	: Radio Frequency
WLAN	: Wireless Local Area Network
WiMAX	: Worldwide Interoperability for Microwave Access
LTE	: Long Term Evolution
GPS	: Global Positioning System
GSM	: Global System for Mobile communication
VSWR	: Voltage Standing Wave Ratio
BW	: Bandwidth
MIMO	: Multiple Input Multiple Output
MNM	: Modal Network Model
MoM	: Method of Moments
FEM	: Finite Element Method
FDTD	: Finite Difference Time Domain
SDT	: Spectral Domain Technique
HPBW	: Half Power Beam Width
RFID	: Radio Frequency Identification
VHF	: Very High Frequency
UHF	: Ultra High Frequency
MRI	: Magnetic Resonance Imaging
PCB	: Printed Circuit Board
MMIC	: Monolithic Microwave Integrated Circuit

CHAPTER I

INTRODUCTION

1.1 PURPOSE OF THE STUDY

The aim of the 'novel triple-band microstrip antenna design' included in this thesis is to design a compact microstrip antenna system with high performance at three distinct resonance frequencies required for complex communication systems. All analyses, findings, and experimental validations from the simulation stage to the implementation phase of the designed antenna are included in this thesis. Additionally, the effects of geometric parameters on the antenna's performance have been thoroughly examined, and parametric analyses are also provided. In addition to this study, general theoretical information about antennas, analysis methods, developmental stages, and working principles of antennas are also included.

The successfully developed triple-band microstrip antenna at the end of this study is suitable for use in various fields such as 4G, 5G, Wi-Fi and WLAN applications, satellite communication, military radars, and GPS systems. It contains three different resonance frequencies available for use with its triple-band structure. Thus, it has the ability to support multiple frequency bands simultaneously. It is an ideal antenna choice for mobile and portable devices where space and weight restrictions are critical.

1.2 HISTORY AND TYPES OF ANTENNAS

The purpose of antennas is to receive or transmit electromagnetic waves. An antenna can be defined as a system that includes supporting structures and protective housing in addition to the main components that carry RF (Radio Frequency) current. The working principle of the antenna is based on converting electrical signals at radio frequencies into electromagnetic waves and radiating them into space or converting electromagnetic waves coming from space into electrical signals [1]. Based on this principle, antennas are classified into two types: receiving antennas and transmitting antennas. Antennas that collect electromagnetic waves from space and transmit them

to the transmission line are called receiving antennas. Those that radiate waves from the transmission line into space are called transmitting antennas. Thus, antennas can be used both as transmitters and receivers, known as the reciprocity principle [2]. Additionally, in the design of receiving antennas, besides passive metal elements, integrated circuits or signal mixers used at microwave and higher frequencies that amplify the signal can also be included [3]. The working principle of antennas is based on electromagnetic theory, which is a result of Maxwell's equations. When this theory is examined, it is seen that when the conductive structure of the antenna is excited by the alternating current passing through the system, it produces electromagnetic waves depending on the frequency of this current. The waves are detected by a distant receiver antenna after being emitted into space by the antenna. Again, based on this theory, it is seen that many antenna designs are based on the principle of resonance. In particular, when resonance occurs, a standing wave is formed in the conductor. Then it spreads in a narrow frequency band [4].

If a specific radiation pattern or beam is expected in antenna design, additional components such as parabolic reflectors, horns, or parasitic elements may be required. To achieve the highest power efficiency and prevent unwanted power reflections, there must be an impedance match between the antenna and the connected transmitter or receiver. To achieve this match, impedance matching devices can be used. These devices are usually basic electronic components such as coils and capacitors. They prevent signal loss by matching the impedance between the antenna and the transmitter or receiver. At the same time, they ensure that the devices operate at optimum performance [5]. Special elements can also be found in the design of the antenna to support this match. In this way, the antenna can receive and send signals more effectively. In addition, the Smith chart is widely used in the impedance matching process. Reflection loss and voltage standing wave ratio (VSWR) are important criteria for evaluating the reflected power and voltage [6]. The energy expended for radiation emission by the antenna is expressed as radiation resistance. Ideally, for most of the power supplied to the antenna to be converted into radiation, the radiation resistance should be high. Furthermore, the polarization of the waves emitted by antennas is also an important factor. This polarization can be linear, circular, or elliptical [7][19].

Directional gain of an antenna is the power radiated by the antenna based on a specific direction, measured in decibels. This gain value indicates the intensity of the

main radiation lobe. The radiation intensity is directly related to this directional gain. It is defined as the average amount of power per unit solid angle (steradian) [1] [20].

The chronology of antenna development has progressed in parallel with advancements in electromagnetic theory and communication technologies. The first steps in this history were taken by Michael Faraday in 1830 when he discovered the existence of electromagnetic waves by moving a magnetic field around a wire loop [2]. Later, Heinrich Hertz's work with radio waves in 1886 continued this historic step by creating an electric spark with a dipole antenna, proving that the resulting waves travelled at the speed of light [3]. In 1901, Guglielmo Marconi sent a signal using a transmitting antenna located in Poldhu, Cornwall. This antenna featured several wires connected to the ground. On the other side of the Atlantic Ocean, in St. John's, Newfoundland, a receiving antenna was set up using a 200-meter wire held by a kite. On December 12, 1901, Marconi and his assistant George Kemp received the letter "S" in Morse code wirelessly transmitted across the Atlantic Ocean [4]. This was the reception of the first transatlantic radio signal. This experiment and technological advancement earned Marconi a Nobel Prize. It demonstrated that the curvature of the Earth was not a disadvantage in radio communication, leading to the global spread of radio communication. Following this experiment, in 1906, Columbia University established a wireless station. They designed a cage consisting of wires suspended in the air as the transmitting antenna [5]. By the 1920s, Yagi-Uda antennas were developed with the goal of optimizing the directional gain, a parametric feature of antennas. The names behind this development were Japanese scientists Hidetsugu Yagi and Shintaro Uda. This type of antenna, providing directional gain, became widely used in television and radio broadcasting [6]. In the 1940s, antenna arrays and parabolic reflectors were developed for use in radar and long-distance communication systems. These antennas became widely used in communication technology due to their high gain and directivity. During this period, horn antenna designs also started to appear. The development of horn antennas continued in parallel with advancements in radar technology [7]. Later, with the outbreak of World War II, antenna technology was actively used, impacting weapon technology during the war. Radio-based detection and tracking technology designed during that period were used by many countries involved in the war [8]. During the war, British physicists invented the cavity magnetron oscillator, providing access to the microwave region. This invention led to the development of second-generation microwave radars in radar technology. The

SCR-584 radar, developed by the MIT Radiation Laboratory, is an example of a microwave radar used for air defence, guiding antiaircraft weapons to the target, operating in the 2.7 to 2.9 GHz frequency range with a 6.6-foot diameter parabolic reflector antenna. All these developments influenced the course of the war and formed the basis of fundamental radio communication systems used in post-war civilian and military technologies [9]. After the war, in 1965, NASA launched the world's first commercial communications satellite, Intelsat I, also known as “Early Bird,” into orbit. The goal was to advance space-based communication. Intelsat I, unlike previous low-orbit satellites, was placed in geosynchronous orbit (22,300 miles high, above the equator). Thus, instant communication was provided from a fixed point on Earth between Europe and North America [10].

The beginning of the history of microstrip antennas is the microstrip patch antenna concept proposed by Deschamps in 1953 [11]. With the development of printed circuit board (PCB) technology in the 1970s, this concept began to gain interest and develop. Howel and Munson were the first to develop practical microstrip antennas. Later, some limitations encountered in the design, such as narrow bandwidth, polarization purity and power carrying capacity, were tried to be optimized. The significant increase in the bandwidth of microstrip antennas was achieved with the aperture coupling feeding technique developed by Sullivan and Schaubert in 1986 [12]. In addition, new substrate materials were used to increase performance. Following all these developments, these antennas began to be widely used in a broad range of applications, from mobile devices to satellites. They have become particularly preferred in applications such as RFID, GPS, television, MIMO systems, radar, remote sensing, and direction finding [11].

When we look at these developments in history, we see that various antenna types and new designs have emerged throughout the period. This diversity usually appears in various combinations to improve a condition or performance requirements or to differ in the field of use. Each type of antenna has its own distinct advantages in its respective field. Constantine A. Balanis’ book, “Antenna Theory: Analysis and Design,” explains many antenna types in detail. The types of antennas particularly covered in this book include dipoles, loop antennas, array antennas, broadband and frequency-independent antennas, aperture antennas, horn and microstrip antennas, and finally, reflector antennas [1]. The simplest and most common antenna type used in telecommunications is Dipole antennas. It is a structure that carries a line current with

only one node at each end. This structure creates a radiation pattern that mimics the radiation pattern of a basic electric dipole. It usually consists of two identical conductive elements. These elements are placed between the feed line connected to the transmitter or receiver. Each half of the antenna is connected to the feed point. This connection determines the radiation pattern and energy distribution of the antenna. Dipole antennas are theoretically considered one of the most basic types of antennas due to their simple structure. They are often used as resonant antennas. Resonant antennas are antennas designed to perform best at a specific frequency. There are variations of these antennas. These variations include short dipole, half-wave dipole, folded dipole, cage dipole. A short dipole antenna is formed by two conductors whose total length ℓ is much shorter than half the wavelength ($1/2\lambda$). It is used in applications where a full half-wavelength dipole would be too large. It is shorter than a resonant antenna (half-wavelength long). Due to the large capacitive reactance at the feed point impedance, it is particularly used as a transmitting antenna. Its design requires a loading coil or other matching network [2].

Another variation, the half-wave dipole antenna, is formed by placing two quarter-wavelength conductors end to end. The total length of this antenna is approximately ($\ell=1/2\lambda$). The current distribution along the length of the dipole is approximately a sinusoidal standing wave. There is a node at the ends and a peak current at the centre (feed point). In this type of antenna, the resistance at the feed point is higher when the dipole is fed from a point other than its centre. The radiation resistance is typically expressed based on the presence of maximum current along the antenna element. For a half-wavelength, this current is also the current at the feed point. When examining the folded dipole antenna, it is seen that this structure consists of two quarter-wavelength conductors connected end to end, with an additional parallel wire joining the two ends. Although the far-field radiation pattern is similar to that of a single-wire dipole, the feed point impedance at resonance is four times greater. The folded dipole has characteristics similar to a full loop antenna, with a wider bandwidth, high feed point impedance, and high efficiency. The radiation pattern of the folded dipole is similar to that of a dipole antenna. A third parallel wire can be added to the design to extend the resonant frequency band. Half-wave folded dipoles are commonly used for FM radio antennas. Among other variations, the cage dipole antenna is designed using thick cylindrical dipole elements made of wires arranged in a "cage" shape to provide wide bandwidth. These types of antennas are used in applications

such as medium wave and short-wave radar and radio telescopes [2]. Although dipole antennas have a simple structure, they can be used as radiating elements in more advanced antenna designs such as Yagi antennas and array antennas. In these designs, dipole antennas serve as feeders [1]. Another type of antenna, loop antennas, is a radio antenna consisting of a cable or electrical conductors in the form of a loop or loops connected to a balanced transmission line. These antennas are divided into two basic designs: loop antennas, which are much smaller than a wavelength and are generally used as receivers, and oscillating loops, which have a circumference of about a wavelength. Small loops are mostly used as receiver antennas at low frequencies but have poor efficiency. They are rarely used because of their low efficiency. They are generally less efficient than full-size antennas. There are some situations where the use of full-size antennas is not possible. For example, due to space constraints or other practical reasons. In such cases, small loop antennas may be a good choice. The radiation pattern of small loop antennas is maximal in the plane of the loops [2].

Small receive loops can be designed as compact antennas optimized for capturing radio waves much longer than their size. When the perimeter is kept to less than $(1/10)$ of a wavelength, they have very distinct directional blanking points where the signal is lost. Another area of optimization is for compact antennas that radiate the signal with minimal inefficiency. Small loops with a perimeter approaching $(1/2)$ of a wavelength, although inefficient, can be optimized for broadcasting purposes [13].

Large loop antennas, with circumferences close to or more than one full wavelength at the operating frequency, are self-resonant at that frequency. Large loop antennas exhibit high efficiency performance in broadcasting and signal reception compared to other types of antennas. These antennas have a self-resonant frequency that is one or more full wavelengths away from their operating frequency. They are particularly suitable for applications requiring long-distance radio communication and high-quality broadcasting because of their strong signal propagation and sensitive signal reception capabilities. The bidirectional radiation pattern of large loop antennas optimizes signal transmission and reception in specific directions by achieving maximum signal strength in both directions perpendicular to the plane of the antenna. [14]. An order of magnitude more efficient than other antenna designs of similar size, these antennas perform well in radio frequency applications. They are often preferred by amateur radio operators, broadcasters, and communications professionals [15].

The halo antenna is often described as a half-wave dipole antenna. Physically, it can be thought of as a twisted circle. The halo antenna falls into the category of a twisted dipole. However, when looking at its radiation pattern, it behaves like a small loop antenna and radiates completely in all directions. The circumference of halo antennas is half a wavelength. The large radiation resistance makes it more functional than small loop antennas. The high radiation resistance of the halo antenna makes it easier to impedance match 50 Ohm coaxial cable. At VHF and higher frequencies, the small diameter of the halo antenna makes it ideal for mobile applications. To make the horizontal radiation pattern more directional, it is possible to make the loop slightly smaller and increase the capacitance between the element ends. This adjustment is also generally effective in reducing upward wasted radiation at VHF frequencies. The halo antenna can be thought of as a dipole bent into a circular shape. The gap in the loop distinguishes it from a small loop antenna because there is no direct current coupling between the ends. However, this distinction does not apply at radio frequencies. The closely twisted ends are capacitively coupled. Radio frequency current flows through this gap as a displacement current. In other words, this gap acts like the tuning capacitor found in small loop antennas, but with lower capacitance [16].

According to the Rayleigh criterion, an antenna's directivity, or the beamwidth of the radio waves it emits, is directly related to the wavelength of the radio waves divided by the antenna's width. Small antennas, about the size of a wavelength, such as quarter-wave monopoles and half-wave dipoles, do not have much directivity (gain). These antennas are omnidirectional antennas that broadcast radio waves over a wide angle [17]. Two general techniques can be used to create a directional antenna that broadcasts radio waves in a narrow beam (high-gain antenna). The first is to change the direction of the radio waves by reflecting them off large metal surfaces or by refracting insulating lenses, or to focus the radio waves from a single low-gain antenna into a beam. The second technique is to use multiple antennas fed from the same transmitter or receiver. This is another type of antenna called an array antenna. The basic operating principle of this antenna is based on the constructive interference of the waves when the peaks and troughs of the waves emitted from the antennas align simultaneously. The energies of the waves add up to form a strong signal. This phenomenon is called constructive interference. An antenna array can radiate a strong signal in a specific direction. On the other hand, if the peak of a wave from one antenna coincides with the trough of a wave from another antenna, these waves weaken or

cancel each other out. This causes the energies of the waves to form a weaker signal. This phenomenon is called destructive interference. An antenna array can reduce signal strength in undesired directions. This principle allows antenna arrays to focus strong signals in a particular direction and block unwanted signals from other directions. Antenna arrays can send signals to the targeted area with high directivity. Conversely, they can minimize interference from other directions [18][25].

An antenna array is a structure in which multiple antennas combined work together to transmit or receive radio waves. This system is used to strengthen multiple antennas in a certain phase. In this way, radio waves are strengthened in the desired direction, while attenuated in the undesired directions. It is preferred to obtain higher gain (directivity) and to ensure that radio waves are spread in a narrow beam. Increasing the number of antenna elements used increases the gain and narrows the beam. Individual antennas, i.e. elements, are usually connected to a single receiver or transmitter via feed lines, and the power elements have a certain phase relationship in these lines. In some designs, more than one transmitter or receiver module is used by connecting them to antenna element groups [1] [2][25].

In periodic array antennas, the elements have the same orientation and the same polarization of the electric field. The array factor ($F(u)$) expresses the radiation pattern of this antenna array and is represented by the following formula:

$$F(u) = \sum_{n=1}^N I_n e^{jkx_n u} \quad (1.1)$$

Here, N represents the number of elements, I_n represents the complex current source, x_n represents the position of the n -th element, k represents the wave number, and $u = \sin(\theta)\cos(\phi)$ defines the expression related to angular variables [1][2]. If the distance between adjacent elements is constant, the array is considered periodic. More specifically, when the distance between antenna elements is half the wavelength ($d = \lambda/2$), the magnitude of the array factor (u) will have a period of 2 in the domain of the variable. The antenna array radiates stronger signals in specific directions. For radiation purposes, the values of the variable (u) should be within the range of $[-1, 1]$, known as the visible space. If the distance between antenna elements is too large, additional lobes, known as grating lobes, may form, causing the reception of unwanted

signals. Therefore, in periodic arrays, the distance between antenna elements should not exceed a certain value to prevent grating lobes from appearing in the visible space. In aperiodic arrays, the distance between the antenna elements is not fixed. Aperiodic arrays provide a cleaner radiation pattern by eliminating the grating lobes for better performance in transmission and reception. Since the array factor in these antennas is a stochastic process, it is calculated over its average [25]. Its formula is as follows:

$$E[F(u)] = \int_{-L/2}^{L/2} f(x) e^{jkxu} dx \quad (1.2)$$

Antenna arrays can be divided into two main categories. The first category includes broadside arrays. In these types of arrays, the main lobe of the radio waves emitted by the antennas is perpendicular to the plane of the array. Radiation occurs in a direction completely horizontal or completely vertical relative to the plane of the array. These types of antennas are fed in phase. The other category is end-fire arrays. In these arrays, the propagation direction is along the line of the antennas. The antennas are fed with a phase difference equal to the distance between adjacent antennas. These arrays usually consist of antennas aligned in a single line. In addition to these two categories, antenna arrays can also be categorized according to the arrangement of the element antennas. Driven Arrays, Collinear Arrays, Planar Arrays, Reflective Arrays, Adaptive Arrays, Parasitic Arrays and Yagi-Uda Antennas are antennas belonging to this category. To briefly mention all of them: In driver arrays, the individual antenna elements connected to the receiver or transmitter are usually of the same type. These elements usually consist of a single driver element, such as a half-wave dipole. Collinear arrays are formed by vertically arranging multiple dipole antennas. These arrays are high-gain antennas that can radiate signals in all directions. Planar arrays have a two-dimensional structure and are mounted in front of a flat reflector or consist of directional antennas. Reflector arrays are antennas in which half-wave dipoles are placed in front of a flat reflector and are commonly used in UHF television and radar antennas. Adaptive arrays are antennas with receiver arrays that optimize the radiation pattern by determining the direction in which the radio waves arrive. In parasitic arrays, only one antenna element is connected to the receiver or transmitter, while the other elements play a role in changing the radiation pattern. Finally, the Yagi-Uda

antenna consists of multiple half-wave dipole elements and is frequently used in television, short-wave communication and radar systems[1][2][13][14].

Array antennas are especially preferred in certain application areas. “Phased Array Radar” (PAR) systems, used in applications such as air traffic control and meteorological radars, use this technology for fast and accurate target detection [7]. In satellite communications, array antennas are used in projects like the “Globalstar” and “Iridium” satellite networks, designed to meet high bandwidth requirements [7]. In mobile communication, the “Massive MIMO” (Multiple Input Multiple Output) technology in 5G has popularized the use of array antennas. In the medical imaging field, array antennas enhance the resolution of MRI devices, enabling more precise diagnoses. This technology is also employed in military defence systems, particularly in advanced sea-based defence platforms like the “Aegis Combat System.” [7]. A horn antenna, also known as a microwave antenna, is designed to direct radio waves into a beam and consists of a horn-shaped metal structure. Typically, a horn antenna includes a rectangular or cylindrical metal tube, called a waveguide, closed on one end, and an open-ended conical or pyramidal horn on the other. Radio waves are transmitted into the waveguide through a coaxial cable. This conductor forms a quarter-wavelength monopole antenna within the waveguide. The monopole antenna directs the radio waves from the waveguide to the end of the horn antenna. The open end of the antenna emits the radio waves in a narrow beam, enabling the antenna to function. These antennas can be used at UHF and microwave frequencies above 300 MHz. The advantages of horn antennas include moderate directivity, wide bandwidth, low losses and tuning. Another prominent advantage is that they can operate over a wide frequency range because they do not contain resonant elements. The usable bandwidth of this antenna is usually around 10:1 and can go up to 20:1. For example, this antenna can operate from 1 GHz to 20 GHz. The input impedance changes slowly across this wide frequency range, providing a low Voltage Standing Wave Ratio (VSWR). Although the gain of horn antennas can reach up to 25 dBi, the typical gain of a horn antenna ranges from 10 to 20 dBi. The operating principle of these antennas is based on the propagation of electromagnetic waves in a conical cavity. A point at the apex, known as the phase centre, is where the wavefront spreads out. The factor that determines the electric and magnetic field pattern is the aperture plane at the mouth of the horn antenna. A disadvantage of this antenna design is the increasing phase error with the flare angle of the antenna. The increasing phase error reduces the gain while

increasing the beamwidth. The gain of these antennas depends on the phase error and the aperture size. In practice, the aperture size is limited to approximately 15 wavelengths. Therefore, the gain is typically around 1000 (30 dBi), and the minimum beamwidth is between 5 and 10 degrees [1][2].

Pyramid Horn antenna is an antenna that is usually used with rectangular waveguides, which is shaped like a four-sided pyramid. It broadcasts linearly polarized radio waves. The E-Plane horn antenna is a sectorial horn antenna extended in the direction of the electric field in the waveguide. The expansion of the horn occurs in the direction the electric field moves. The H-plane horn antenna is a sectorial horn antenna extended in the direction of the magnetic field within the waveguide. More specifically, the expansion of the horn occurs in the direction the magnetic field moves. The conical horn antenna is cone-shaped with a circular cross-section used with cylindrical waveguides. The exponential horn antenna has a design with two-dimensional cross-sections that are either pyramidal or conical with tapered sides. It is generally preferred in applications requiring high performance [1][2][8].

Since horn antennas have very low losses, directivity can be considered approximately equal to gain. The following formula can be used to calculate the gain in these conical antennas.

$$G = \left(\frac{\pi d}{\lambda}\right)^2 e_A \quad (1.3)$$

For pyramidal antennas, this formula is as follows:

$$G = \frac{4\pi A}{\lambda^2} e_A \quad (1.4)$$

The area of the aperture A , the diameter d of a conical horn's aperture, and the wavelength λ represent key parameters. The variable e_A , which takes a value between 0 and 1, represents the aperture efficiency, a dimensionless parameter. In practice, the aperture efficiency of horn antennas varies between 0.4 and 0.8 [1][2][8].

Another type of antenna, the reflector antenna, reflects electromagnetic waves. It can be used as a stand-alone device to direct radio frequency (RF) energy, or it can be integrated as part of an antenna assembly. The reflector allows the antenna to

radiate signals in a more focused and directional manner. It allows the signal to reach greater distances and be received more powerfully. A corner reflector is a component of UHF television antennas that reflects incoming signals back in the direction they came from and is commonly used in radar systems. A flat reflector functions like a mirror, reflecting signals and is often used as a passive repeater. There are several design criteria to consider when designing these antennas [1][2][8].

Briefly explaining these criteria: the size of the reflector is important because different sizes exhibit different performance characteristics. Feed blockage occurs when some of the feed energy is reflected back to the feed antenna and does not contribute to the main beam. The illumination cone reduces the feed illumination at the edges of the reflector. In order to prevent signals from forming in undesirable polarization directions, attention should be paid to the cross-polarization criterion. Another criterion that should be taken into consideration is the incompatibility of the antenna and the feed line. Irregularity of the amplitude and phase distribution of the antenna is also an undesirable performance and a criterion that should be optimized [1][2]. While antennas emit maximum power in the main beam direction, they can also emit lower levels of power in undesirable directions. This power emission in undesirable directions is called “side lobe”. The rise of the side lobes reduces the gain of the antenna in the main beam direction, since some of the total power of the antenna is distributed to the side lobes. This distribution reduces the focused power of the antenna, and therefore its efficiency. The side lobes also affect the system noise temperature. The system noise temperature is a measure of the background noise that affects the quality of the signals received by the antenna. When the side lobes increase, the antenna receives more noise signals, reducing the signal-to-noise ratio and reducing communication quality. In antenna design, it is important to minimize the side lobes and other gain-reducing factors. These factors include aperture obstruction, reflective surface aberrations, cross-polarization, feed losses, and antenna feed mismatch. Such problems can adversely affect the antenna's radiation pattern and overall performance [1][2][14].

As important as selecting the right antenna for the intended application is, it is equally crucial to feed these antennas correctly and optimally for system performance. The quality of the signals received and transmitted by the antennas depends on the feeding method. An appropriate feeding system optimizes the potential of the antenna and the system, ensuring clear communication. Therefore, examining feeding methods

after considering antenna types will contribute to the optimization of communication systems [1][2].

If we mention to the antenna feed system, according to the basic working principle, the cable or transmission line that connects the antenna to the radio transmitter or receiver is called the "feed line". In a broadcasting antenna, the feed line carries the radio frequency current from the transmitter to the antenna, and thus radio waves are emitted. In receiving antennas, the small RF voltage created by the radio wave on the antenna is transmitted to the receiver and this signal is processed [2][21][22].

If we also mention to the components of the antenna feed system and how various antenna types are connected, in transmitter systems, all the components located between the final amplifier and the feed point of the antenna are included in the antenna feed system. Similarly, in receiver systems, every component between the antenna and the input terminals of the receiver is part of the antenna feed system. In addition, in some antenna designs such as parabolic dish antennas, the feed antenna and the feed pipe are also included in this feed system [2].

To carry RF current efficiently, feed lines are made of a special type of cable known as a transmission line. Coaxial cable, twin-conductor cable, and waveguide are the most preferred types of feed lines at microwave frequencies. These types of cables are frequently used in designs. When we examine these cables in more detail, the flat and ribbon-shaped cable with two ends consists of two wire conductors placed parallel to each other and at a fixed distance from each other and is used to connect radio and television receivers to antennas. Although it is commonly used in low-power transmitters and amateur radio transmitters, modern television receivers today mostly use coaxial cable for feeding purposes [1][2]. The working principle of the twin-conductor cable is that the current flowing through the two wires is the same magnitude but opposite in direction because the distance between the two wires is shorter than the wavelength of the RF signal passing over it. Since both wires carry currents of equal magnitude and in the same direction, these currents can neutralize external radio frequency interference or noise. This feature provides a clean signal transmission without the cables being affected by external factors. This design allows the antenna to operate more efficiently because it reduces unwanted signals other than those emitted or received by the antenna. Due to this feature, twin-conductor cables are

generally an ideal feeder cable for low-power transmitters and receivers [1][2][21][22].

Coaxial cable, particularly used at frequencies lower than microwave frequencies, is a common type of feed line. This cable typically consists of a conductive copper wire shielded by copper or aluminium, with insulating material placed between the two conductors to maintain a constant distance. In other words, from the inside out, it is designed as a conductive copper wire, insulating material, and a copper or aluminium shield. The outermost part of the cable is a plastic sheath. In applications requiring high power, the shield conductor can be a rigid or flexible metal tube, and it may also contain a compressed gas like nitrogen. These structural features allow coaxial cable to transmit signals optimally without being affected by unwanted electromagnetic fields. The shield conductor is usually connected to electrical ground. The currents flowing through the central copper conductor are balanced by currents moving along the inner surface of the shield in opposite directions. For the coaxial cable to function as a "Balanced Line," it is necessary to prevent current on the outer surface. The ability of the shield conductor to isolate the internal currents from external electromagnetic fields is one of the greatest advantages of coaxial cable. This feature prevents the cable from being affected by interference from nearby metal objects or external factors by blocking currents on the outer surface. Thus, coaxial cable preserves signal integrity and provides cleaner transmission [1][2][21][22].

Waveguides are preferred at high frequencies because they have less power loss than other feed lines. Waveguides, which have a hollow metallic structure, can usually be round or square. These guides are often pressurized with nitrogen gas to prevent moisture accumulation from degrading the signal quality. RF signals are transmitted through the metal walls of the waveguide, much like sound waves through a tube. These metal walls protect the signal, prevent leaks, and isolate the waveguide from external influences. To simplify maintenance, the output section of the transmitter or the RF front section of the receiver are usually placed directly on the antenna. The signal is then transmitted via coaxial cable to the rest of the transmitter or receiver operating at a lower frequency [1][2][4][21][22].

Impedance matching is the most important point for the antenna and transmitter to work in harmony with maximum efficiency. Transmitters are usually designed with an impedance of 50 ohms. The impedance of the antenna should be compatible with this value and the characteristic impedance of the transmission line. This compatibility

ensures that the power is transferred to the antenna at the highest rate. It is also important in minimizing the reflected power. One of the basic formulas used in impedance matching is the Standing Wave Ratio (SWR) and reflection coefficient calculation. SWR is the ratio between the maximum and minimum voltage (or current) values on a transmission line or antenna. It provides an understanding of the matching of the antenna impedance to the transmission line impedance. Ideally, its value is expected to be close to one. The formula for the relationship between SWR and gamma is as follows:

$$SWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (1.5)$$

The symbol Γ in this equation represents the reflection coefficient. The formula that allows us to understand the relationship between the load impedance (Z_L) and the characteristic impedance (Z_0) is as follows:

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \quad (1.6)$$

For an optimized match, the load impedance must be equal to the characteristic impedance. In this case, the reflection coefficient is zero and the SWR value is 1. Impedance matching is an important issue in radio frequency (RF) systems to ensure maximum power transfer between different components. Matching the impedance of the source to the impedance of the load is important when efficient energy transfer is desired. It is necessary to reduce signal reflection and distortion. When this is achieved, the performance and range of wireless communication systems increase [1][2][4].

1.3 ANTENNA PARAMETERS

Although many parameters determine an antenna's performance and efficiency, some of these parameters are interconnected. Therefore, it is generally not necessary to test all parameters for performance analysis. Since antenna parameters are indicators of operational efficiency, analysing these parameters during the design process and optimizing according to requirements is important. Today, IEEE antenna terminology

standards exist. Designs are generally implemented within the limits of these standards [1][2].

One of these parameters is the radiation pattern. This parameter helps us understand how much power the antenna transmits in different directions. More specifically, the radiation pattern in the far-field region is expressed as a function according to directional coordinates. This definition is taken from IEEE Antenna Terminology Standards [1][2].

The graph of this parameter typically shows normalized power patterns and normalized fields according to the maximum value, although logarithmic scale or decibel plots also display the details of the pattern's very small features, such as minor lobes. The pattern normalized to the maximum value makes it easier to compare patterns. The logarithmic scale is used to show the low value parts of the pattern, i.e. the small lobes, in more detail. The power pattern on the linear scale is a graph of the square of the magnitude of the electric or magnetic field, which shows the energy distribution of the antenna, against angular space. To explain the lobes mentioned in this paragraph in more detail, the different sections in the graphs showing the distribution of the energy radiated by the antenna in space are called lobes. They are classified as main or major lobes, secondary or minor lobes, side lobes and back lobes. The main lobe is the main propagation direction where the antenna aims its intense radiation. The secondary lobes are the parts of the antenna that emit radiation outside the main lobe in unwanted directions. They are generally less intense. Side lobes are located next to the main lobe. The side lobe is located in the hemisphere of the main lobe, while the back lobe is at an angle of approximately 180 degrees to the antenna beam direction. By considering these lobes, we can analyse the energy radiated by the antenna in a particular direction. The goal is to minimize the level of side lobes as much as possible because otherwise, they can cause unwanted signal interference or noise. In a radar system project, the presence of side lobes can result in false target indications. We can understand how much weaker the side lobes are compared to the main lobe by the ratio of the power density in the side lobes to the power density in the main lobe [1][2][14].

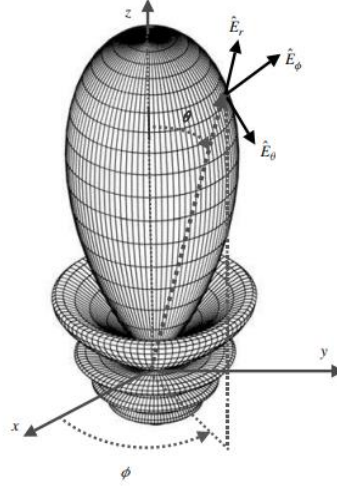


Figure 1: Normalized three-dimensional amplitude field pattern [1]

The total magnitude of the electric field is calculated using the following formula, considering the three electric field components (E_r , E_θ , E_ϕ) at each observation point:

$$|E| = \sqrt{|E_r|^2 + |E_\theta|^2 + |E_\phi|^2} \quad (1.7)$$

Here, E_r is the radial component, and E_θ and E_ϕ are the other two angular components [1].

Directivity is another important parameter in antenna design and analysis. The definition of this parameter has been made compatible with all international standards and published in the IEEE antenna terminology standard definitions as "the ratio of the radiation intensity of the antenna in one direction to the radiation intensity in all other directions". In other words, it is the ratio of the directivity of a non-omnidirectional source to the radiation intensity of an isotropic source that emits equal radiation in all directions. This ratio shows how "concentrated" or "focused" the antenna is in that direction. The formula that helps us understand the directivity parameter mathematically is as follows:

$$D = \frac{U(\theta, \phi)}{U_0} = \frac{4\pi U}{P_{rad}} \quad (1.8)$$

Where D is the directivity, P_{rad} is total radiated power (W), $U(\theta, \phi)$ is the radiation intensity in a specific direction, and U_0 is the radiation intensity of an isotropic source [1][2][23][24].

In antennas with orthogonal polarization components, partial directivity is defined as the ratio of the radiation intensity in a specific direction and polarization to the total radiation intensity averaged over all directions. Simply put, it represents how “focused” the antenna is in a particular direction and polarization. The total directivity of an antenna is the sum of the partial directivities calculated for its two orthogonal polarizations in a specific direction. Using the spherical coordinate system, the total maximum directivity (D_0) for the orthogonal components θ and ϕ of the antenna can be expressed as [1][2]:

$$D_0 = D_\theta + D_\phi \quad (1.9)$$

Another important parameter is antenna efficiency. If we need to define antenna efficiency, it is the ratio of the power radiated by the antenna to the input power given to the antenna. In an optimum antenna design, the input power given is expected to radiate the losses in the transmission line in the least way. This is directly related to the efficiency of the antenna. In general, the formula expressing antenna efficiency is as follows:

$$e_0 = e_r e_c e_d \quad (1.10)$$

In this formula, e_0 represents the total efficiency, e_r represents reflection efficiency, e_c represents conduction efficiency, and e_d represents dielectric efficiency. However, since e_c and e_d values are difficult to calculate, they are usually determined experimentally. An alternative formula using the voltage reflection coefficient (Γ) is often preferred [1][2]:

$$e_0 = e_{cd}(1 - |\Gamma|^2) \quad (1.11)$$

Another parameter regarding the performance of antennas is the gain. Gain and directivity parameters are closely related, but directivity only shows the directional

properties of the antenna and is expressed graphically. Gain describes efficiency and directivity. In more clear terms, the gain of the antenna shows how effectively the antenna converts the input power into radiation and focuses the radiation on a certain direction. In a receiving antenna, this is how efficiently it converts the incoming radio waves into electrical power. The mathematical expression of this parameter is the ratio of the radiation intensity emitted by the antenna in a certain direction to the power assumed to be emitted isotopically by the antenna. The formula:

$$G = \frac{4\pi \times U(\theta, \phi)}{P_{in}} \text{ (dimensionless)} \quad (1.12)$$

Where $G(\theta, \phi)$ is the gain in a specific direction, $U(\theta, \phi)$ is the radiation intensity in that direction, and P_{in} is the input power to the antenna [1][2].

The direction function plot of gain should not be confused with the directivity plot, which does not consider the radiation efficiency of the antenna [1][2][23][24].

The bandwidth parameter is important so that we can evaluate the performance of the antenna at different frequencies. This parameter helps us understand at which frequencies the antenna performs effectively. Another way to define it is as the frequency range around the centre frequency where the antenna characteristics meet the standards. In wideband antennas, bandwidth is expressed as the ratio between the upper and lower limits of the accepted operating frequencies. In narrowband antennas, bandwidth is expressed as the percentage of the difference between the operating frequencies to the center frequency. For example, 5% bandwidth means that the frequency difference is 5% of the bandwidth center frequency [1][2][14][22].

There are many factors that affect the bandwidth of an antenna, such as input impedance, radiation pattern, gain, and polarization. Since each of these factors affects bandwidth differently, bandwidth cannot be defined by a single property. Optimization is usually performed according to the design needs. Since bandwidth is not limited by a specific parameter, it can be adjusted to suit the requirements of a specific application. Pattern bandwidth and impedance bandwidth reveal different properties of the antenna such as pattern and input impedance. It helps us understand the change of the antenna's radiation pattern in a certain frequency range. If the antenna's properties such as gain, side lobe level, beam width, polarization and beam direction remain within acceptable limits in a certain frequency range, this range is considered

as the antenna's pattern bandwidth. Impedance Bandwidth allows us to analyse the response of the antenna's input impedance and radiation efficiency to frequency changes. If the antenna's input impedance remains constant in a certain frequency range, it is called the antenna's impedance bandwidth [1][2][6][23][24].

Another important parameter is polarization. The orientation of the transmitted radio waves' electric field is determined by the antenna's orientation and physical structure. A vertically oriented dipole antenna, for example, results in vertical polarization, while the same antenna turned sideways would result in horizontal polarization. Polarization is susceptible to reflections, especially by radio waves reflected from the ionosphere. However, horizontally or vertically polarized transmissions (for line-of-sight communication or ground wave propagation) generally retain the same polarization state if they reach the receiver directly without obstruction. The principle of deriving the polarization of an antenna from geometry is based on the fact that if the antenna conductor is seen to lie in a straight line when viewed from the reference point, linear polarization is produced in that direction. However, more general cases require analysis. For example, a horizontally mounted helical antenna might appear to produce horizontal polarization when viewed from a distant location. Conversely, when viewed from an aircraft looking downwards, the antenna might appear to produce elliptical polarization. In other words, the polarization state can vary with the transmission frequency [1][2][6].

Since the electric field vector draws an ellipse in each cycle, polarization is most generally elliptical. Linear polarization occurs when the radio wave emits an electric field in a single direction, while circular polarization occurs when the radio wave rotates around the electric field propagation axis. To go into a little more detail on this subject, linear polarization occurs if it has a component or if it meets the requirement of being in the same phase or 180 degrees and multiples out of phase in the case of two perpendicular linear component. In order for circular polarization to occur, the field must have two perpendicular components of the same amplitude and at the same time, these two components must have a time phase difference of odd multiples of 90 degrees. The requirements that must be met to obtain elliptical polarization are that the field must have two perpendicular linear components of the same or different amplitudes. When the two components are not of equal magnitude, their time-phase difference must be 0 degrees or multiples of 180 degrees to avoid linear polarization. Conversely, if the components have equal magnitude, their time-

phase difference should not be odd multiples of 90 degrees, unlike the previous scenario [1][2][8]. For optimum reception performance, polarization is a critical detail to consider. It is important that the receiving antenna matches the polarization of the transmitted wave to prevent any loss in signal strength. In the case of polarization mismatch, a situation occurs when the polarization difference between the receiving antenna and the transmitting antenna is such that the power the antenna will receive from the incoming signal is not at its maximum. Due to this phenomenon, the power drawn decreases. The formula expressing the electric field of the incoming wave is:

$$E_i = \hat{\rho}_w E_i \quad (1.13)$$

In this formula, p_w is the unit vector of the electric field. To express the electric field polarization of the receiving antenna, this formula is used:

$$E_a = \hat{\rho}_a E_a \quad (1.14)$$

In this formula, p_a is the unit vector of the antenna. To mathematically define the polarization loss factor, we need this formula:

$$PLF = |\hat{\rho}_w \cdot \hat{\rho}_a|^2 = |\cos \psi_p|^2 \quad (1.15)$$

In this formula, ψ_p is the angle between the two-unit vectors [1][2]. Polarization efficiency is the metric used to describe the polarization characteristics of a wave or antenna and indicates how well it matches the polarization of the incoming wave. It is defined as the ratio of the power received by the antenna from a randomly polarized plane wave to the power it would receive from a plane wave with polarization optimized for maximum power reception. The mathematical expression of this measure is:

$$p_e = \frac{|\vec{e} \cdot \vec{E}_{inc}|^2}{|\vec{e}|^2 |\vec{E}_{inc}|^2} \quad (1.16)$$

In this formula, e represents the vector effective length of the antenna, which includes the antenna's physical characteristics such as size, shape, and polarization, while E_{inc} represents the incoming electric field [1][2][23][24].

Another important parameter in the antenna design subject is the input impedance parameter. An antenna has various definitions such as the ratio of the electric field to the magnetic field at a point or the ratio of the voltage at its terminals to the current. The input impedance of an antenna consists of two parts. These are resistance and reactance. Resistance is the radiation resistance, which represents the antenna's ability to radiate electromagnetic energy as radiation, and the loss resistance, which expresses the energy lost as heat. Reactance, which affects the resonant frequency and bandwidth, allows us to analyze the inductive or capacitive properties of the antenna. The input impedance, which determines the optimization of the antenna with the transmission line and other equipment, should ideally be compatible with the characteristic impedance of the transmission line. Since the input impedance of the antenna depends on the frequency, the match is optimal only in a certain frequency range. This parameter directly affects the efficiency, bandwidth and overall performance of the antenna [1][2][4][6]. Some important parameters that should be considered and analysed in antenna design are explained. In addition to these, there may be other parameters that need to be considered according to the needs of the design. Some of these are radiated power density, radiated intensity, beam width and efficiency, antenna radiated efficiency and antenna temperature [1][2][4].

CHAPTER II

MICROSTRIP ANTENNAS

2.1 HISTORY OF MICROSTRIP ANTENNAS

The initial emergence of microstrip antennas dates back to 1950. The first concept of this antenna was created by George H. Deschamps in 1953. By 1955, Gutton and Baissinot in France had patented this antenna. However, despite these developments, it took twenty years for the microstrip antenna (MSA) concept to be used in practical applications. This was driven by the need for technological advances such as the development of printed circuit board (PCB) technology, progress in materials science, and improvements in antenna design and modelling techniques. Microstrip antennas began to gain acceptance in the 1970s. Although the initial designs and theoretical models emerged in the 1950s, microstrip antennas came back into focus in the 1970s due to the need for low-profile, lightweight, easy-to-manufacture, cost-effective antennas that could conform to vehicle surfaces. In 1972, following these developments, Bob Munson designed microstrip antennas based on the principle of placing a metal patch on a dielectric substrate with a ground plane on the other side of the substrate. He then optimized them for use at microwave frequencies and experimented with patches of various shapes. The primary reason for Munson's invention was the need for low-profile, lightweight, easily manufacturable, and integrable antennas. Bob Munson's step was significant in antenna technology in line with miniaturization. With the widespread adoption of microstrip antennas, certain challenges in their design began to surface. These limitations included bandwidth and low gain. To overcome these limitations, various optimization studies were conducted. These studies included increasing the substrate thickness of the antennas and decreasing the permittivity value to expand the bandwidth. In addition, other problems encountered were low efficiency, narrow bandwidth and spurious feed radiation due to surface waves. Historically, various feed techniques and antenna geometries have been developed to overcome these problems. In addition, optimization methods such as metaheuristic algorithms have been used to improve

the performance of antennas. In parallel with these developments, different concepts such as MSAs, antenna arrays, and high gain and directivity by combining multiple antenna elements have been used to overcome these limitations [15][26][27][28].

2.2 GENERAL CONCEPT OF MIKROSTRIP ANTENNAS

Regarding the general concept of microstrip antennas (MSAs), a metal patch, much smaller than the free space wavelength ($t \ll \lambda$), is placed on a ground plane. Additionally, the thickness of the substrate material is usually designed to be between 0.003λ and 0.05λ ($0.003\lambda < h < 0.05\lambda$) [1][2][15]. Microstrip patch antennas are designed to operate at a specific frequency. The radiation pattern of the antenna indicates the direction and intensity of the energy radiated by the antenna. The highest point in this pattern is where the antenna radiates the most energy. This point is usually located in a direction perpendicular to the surface of the antenna. To put it more clearly, when designing the antenna, the aim is to direct the energy towards this maximum point. The “mode” inside the antenna is the electromagnetic wave pattern that causes the antenna to resonate at a specific frequency. In order for a microstrip patch antenna to operate effectively, this mode must be excited correctly. The excitation of the mode depends on factors such as the geometry of the antenna, its dimensions, and the materials used, and is an important step in the antenna design process [1][2][15].

The length, L , of the rectangular patch is typically between $\lambda/3$ and $\lambda/2$ ($\lambda/3 < L < \lambda/2$). The strip, or patch, is separated from the ground plane by a dielectric material. The dielectric constant of the material used in these designs is important. The dielectric constant of this material is generally chosen to be between 2.2 and 12 ($2.2 < \epsilon_r < 12$). The efficiency in this selection is optimally achieved with thick substrates with a dielectric constant close to the lower end of this range. This is because thick substrates with a low dielectric constant loosely bind the radiation fields of the antenna, helping the antenna to radiate more effectively into space, thus providing better efficiency and wider bandwidth for the antenna. However, these substrates require a larger antenna element, which results in increased physical size. In contrast, thin substrates with a high dielectric constant confine the electric field more tightly within the substrate. This reduces unwanted radiation or electromagnetic interference, allowing signals to propagate through the substrate in a more controlled manner. However, these substrates introduce more loss, reducing efficiency and limiting bandwidth. In the design of microstrip antennas and microwave circuits, optimizing antenna

performance with circuit size and efficiency is an important part of the design. Often, the desired requirement is to both maximize antenna performance and keep the size of the circuit elements as small as possible. This is often a compromise and an important part of the design process [1][2][15].

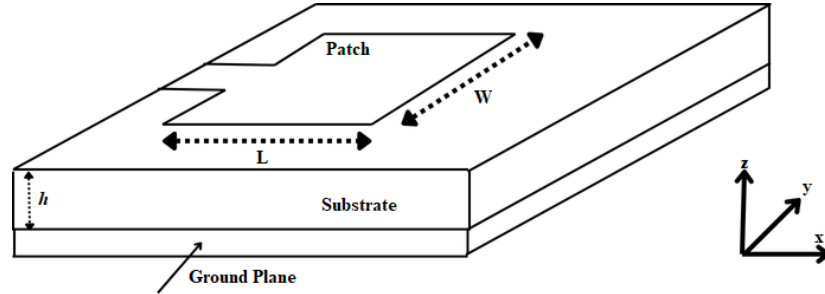


Figure 2: Basic Concept of a Microstrip Antenna

Radiating elements and feed lines on a dielectric substrate are commonly photo-etched on a microstrip antenna. The shape of the radiating patch can be designed as square, dipole, rectangular, triangular, elliptical, or any other shape, although square, rectangular, dipole, and circular patches are preferred due to their low cross-polarization radiation and simplicity of manufacture. Microstrip dipoles have the advantage over other shapes in terms of bandwidth. Microstrip antennas have polarization properties that determine the direction of propagation of electromagnetic waves. Depending on the design of the antenna, it can be linear or circular. These polarizations can be achieved by a single antenna element or by antenna arrays combining multiple elements. These polarizations can be achieved by a single antenna element or by antenna arrays combining multiple elements. These polarizations can be achieved by a single antenna element or by antenna arrays combining multiple elements [1][2]. Antenna arrays can diversify the directions in which the antenna can send and receive signals by using different feed points, thereby expanding the coverage area. In addition, antenna arrays achieve high directivity by concentrating signals in a more optimized direction. This antenna system can be used in applications where wide coverage and high signal quality are important [2][6]. In the design of microstrip antenna systems, it is important to optimize the performance of the antenna as well as the circuit design in which it is integrated. Common methods used to feed microstrip antennas include microstrip line, coaxial probe, proximity coupling (Electromagnetic Coupling), and aperture coupling [15][29].

The microstrip feed line consists of a conductive strip, but it is narrower than the patch. While this feed type is easy to model and manufacture, surface waves and spurious radiation, which limit the design bandwidth by approximately 2-5%, increase when the substrate thickness is increased [15][29]. The coaxial probe feed has low spurious radiation and is easy to manufacture and apply. The inner conductor of this cable is connected to the patch, while the outer conductor is connected to the ground plane. The disadvantage of this feed type is its narrow bandwidth. In cases where $h > 0.02\lambda$, i.e., with thick substrates, modelling becomes difficult. Cross-polarization radiation problems can occur in both of these feed types. Cross-polarization radiation means the antenna emits signals in an unwanted polarization plane, leading to a decrease in antenna performance [4][29]. To reduce this problem, a non-contact aperture coupling feed type has been developed. However, this feed type is difficult to manufacture and has a low bandwidth. On the contrary, spurious radiation is relatively more acceptable. In the non-contact aperture coupling method, the feed point of the antenna receives energy through an aperture or slot structure near the antenna surface. This opening creates a path for electromagnetic waves to pass through. The feed point allows energy to be transmitted to the surface of the antenna through this structure. Thus, energy transfer is achieved without direct contact with the surface of the antenna [15][29].

With the development of modern printing technology, microstrip antennas, which have become easier to produce and more widespread, have many advantages. In addition to their low profile, they can be frequently used on both planar and non-planar surfaces. When mounted on fixed surfaces, higher durability is achieved. They are simple and inexpensive to manufacture and compatible with Monolithic Microwave Integrated Circuit (MMIC) designs [15][30]. This combination is especially common in wireless communication systems. MMICs can be used to feed the RF components of microstrip antennas, thus improving antenna efficiency and performance. Combining MMIC design with microstrip antennas is important for creating compact and high-performance wireless communication devices. This integration is particularly sought after in fields such as satellite communications, radar systems, and mobile communications [7][8]. The use of MMICs with microstrip antennas reduces the size and weight of systems while enhancing system performance and reliability. Microstrip antennas can vary in impedance, pattern, polarization, and resonance frequency with the appropriate patch shape design and mode selection

[2][15]. Microstrip antennas, as mentioned above, usually consist of a patch and a ground plane. By adding loads between these two main sections, compatible elements can be designed that can change various characteristics of the antenna [1]. The loads can be passive or active electronic components such as pins or varactor diodes. The pins can be used to change the resonant frequency of the antenna. This allows the antenna to operate in different frequency bands [3]. Varactor diodes are voltage-controlled capacitors. They are used to adjust the impedance of the antenna. The loads mentioned can change the polarization and pattern of the antenna [9]. Polarization refers to the direction of the electric field vector of the antenna's electromagnetic waves. The pattern describes the distribution of the antenna's radiation in space. In other words, these loads can control the power emitted by the antenna in a certain direction. These adaptive elements enable the antenna to adapt to different applications and improve its performance. Similarly, by changing the impedance, polarization, or pattern of the antenna, signal quality can be enhanced, or the antenna can be made to radiate more power in specific directions [1][15][31].

These antennas have some disadvantages besides all the mentioned advantages. The most important of these disadvantages are low efficiency and low power. Microstrip antennas generally have low efficiency due to surface waves and dielectric losses that cause some of the total radiation power to spread in unhelpful directions [1][4]. The gain of the antenna is limited depending on its size and design. Another disadvantage is its narrow bandwidth. Although narrow bandwidth is desired in government projects, this situation restricts the antenna from operating at different frequencies [1][6]. This problem can be optimized by using methods such as increasing the thickness of the base material. However, it is important to note that increasing the substrate thickness also increases the formation of surface waves, which is generally undesirable. Therefore, the design can be optimized using slots [15].

Among the disadvantages of microstrip antennas, the narrow bandwidth (BW) is a limiting factor for their application. BW is the frequency range in which the antenna can transmit and receive signals while maintaining its performance [1][15]. VSWR (Voltage Standing Wave Ratio) criterion is defined as the ratio of the maximum and minimum voltage values at the antenna's input. It provides us with an understanding of the antenna's ability to transmit power. Generally, this ratio is expressed as 1:1. Additionally, a low ratio indicates good matching [4][7]. Input impedance is the electrical resistance of the antenna at a specific frequency. The input

impedance's compatibility with frequency affects the bandwidth. Radiation parameters are also parameters that need to be considered for BW. These parameters include the antenna's radiation pattern, gain and efficiency [1][2]. AR (Axial Ratio) This is the ratio that defines the bandwidth in circularly polarized antennas. Ideally, it should be close to the value of "1", which indicates that both polarization components are of equal strength [15]. If it is observed that the axial ratio remains constant within a certain range of values, the desired performance of the antenna's circular polarization can be maintained within a certain frequency range. This frequency range is also called the antenna's circular polarization bandwidth. To summarize the definitions in this paragraph, BW can be defined in terms of the antenna's VSWR, the input impedance that changes with frequency or the radiation parameters. There are some formulas and relationships used in bandwidth calculation [1][15].

There are some formulas and relationships used in bandwidth calculations. The bandwidth of microstrip antennas is inversely proportional to the quality factor (Q). The mathematical formula that gives this relationship is as follows:

$$BW = \frac{VSWR - 1}{Q\sqrt{VSWR}} \quad (2.1)$$

This formula calculates the VSWR using the input reflection coefficient (Γ) as follows:

$$VSWR = \frac{1 + |\Gamma|}{1 - |\Gamma|} \quad (2.2)$$

Γ is a measure of the reflected signal at the antenna's feed point. The formula was mentioned in previous sections. It is calculated using the antenna's input impedance and the characteristic impedance of the feed line [1][2][14].

The bandwidth of an antenna is defined as the frequency range where the VSWR is less than 2. This statement, which means that the ratio of the maximum and minimum voltage values at the antenna input is less than 2, also allows us to conclude that the antenna is well matched. In designs used in sensitive applications, the VSWR can be expected to be less than 1.5, so that the antenna is more matched, and the reflected power is less. A VSWR of 2 means that about 11% of the power sent to the

antenna is reflected, while a VSWR of 1.5 means that the reflected power is about 4% [1][2][15].

The relationship and conversion between BW and VSWR can be done with the following formula:

$$\frac{BW_1}{BW_2} = \frac{(VSWR_1 - 1)\sqrt{VSWR_1}}{(VSWR_2 - 1)\sqrt{VSWR_2}} \quad (2.3)$$

BW_1 corresponds to $VSWR_1$, and similarly, BW_2 corresponds to $VSWR_2$ [15].

To explain the relationship between bandwidth (BW) and substrate thickness and dielectric constant, it is observed that in single patch antennas, as the substrate thickness increases, the BW value increases. Conversely, as the dielectric constant (ϵ_r) decreases, the BW increases. The formula expressing this relationship is:

$$\%BW = \frac{C \cdot h}{\lambda_0 \cdot \sqrt{\epsilon_r}} \quad (2.4)$$

(%BW) represents the percentage bandwidth of the antenna, (C) is a constant that varies depending on the design of the antenna and the properties of the substrate used, (h) represents the substrate thickness, and (λ_0) represents the wavelength in free space [15].

To calculate the percentage bandwidth in terms of the dimensions of the antenna and the physical properties of the substrate, there is a mathematical expression. In this formula, the percentage bandwidth of the antenna is expressed in terms of the antenna's width (W), length (L), substrate thickness (h), free-space wavelength (λ_0), and the substrate's dielectric constant (ϵ_r), and is given as follows:

$$\%BW = \frac{A \cdot h}{\lambda_0 \cdot \sqrt{\epsilon_r} \cdot \sqrt{\frac{W}{L}}} \quad (2.5)$$

A in this formula is a constant that varies depending on the thickness ratio of the substrate [15].

As mentioned above, BW does not only depend on electrical properties such as VSWR or impedance. It is related to the radiation properties of the antenna. Radiation parameters related to the signal strength of the antenna include gain, Half Power Beam Width (HPBW) and Side Lobe Levels. HPBW measures the width of the main lobe in the antenna's radiation pattern and indicates the direction of the signal that the antenna radiates at its highest power level. HPBW allows us to analyse the angular distance between two points where the power of the main lobe falls to half of its maximum value. The bandwidth is defined within the frequency range where radiation parameters remain within certain minimum and maximum limits. In other words, the radiation bandwidth of the antenna is defined within the frequency range where the antenna's gain, HPBW, and side lobe levels remain constant while maintaining performance standards [1][6][15].

The directivity parameter, which is directly related to the antenna's gain, is also related to BW. An antenna with a wide bandwidth typically has a lower directivity value because it radiates energy over a broader frequency range. Conversely, high directivity creates a focused radiation pattern, resulting in a narrower BW. The formula that helps us calculate directivity is as follows:

$$D \approx 0.2W + 6.6 + 10 \log \left(\frac{x^{1.6}}{\sqrt{\epsilon_r}} \right) C \text{ dB} \quad (2.6)$$

D represents the directivity of the antenna, W is the width of the antenna, X and C are specific constants, and ϵ_r is the dielectric constant of the substrate [1][2][15].

Various techniques have been developed to increase BW. These methods include Modified Shape Patches, Planar Multiresonator Configurations, Multilayer Configurations, Stacked Multiresonator MSAs, Impedance-Matching Networks for Broadband MSAs, Log-Periodic MSA Configurations and Ferrite Substrate-Based Broadband MSA [32]. To give a brief information about these methods, Modified Shape Patches are a method of increasing BW by modifying regular MSA structures into rectangular rings and circular rings. For example, when a U-shaped slot is cut into a rectangular patch, it provides about 40% BW for $VSWR \leq 2$ [15][32]. Planar Multiple Resonator Configurations, planar, sequentially tuned multiple resonators, as in multi-stage tuned circuits, provide large BW. Multi-Layer Configurations employ the design principle of stacking two or more patches in different dielectric layers. In

Stacked Multiple Resonator MSAs, BW and gain are increased by combining Planar and stacked multiple resonator techniques [15][32]. Impedance matching networks are utilized to enhance the BW of the MSA to around 10%. To achieve a multi-octave bandwidth, the log-periodic antenna design is incorporated into the MSA. [15]. The multi-resonant behavior of a patch on a ferrite substrate provides a wide BW of approximately three octaves by changing the magnetic field [15][32]. Bandwidth is related to quality factor and efficiency. They cannot be optimized independently. Therefore, they should all be considered for optimum antenna performance. Although the relationship between gain and bandwidth has been touched upon in the previous paragraphs, it is necessary to elaborate on this subject in more detail. Quality factor is a performance measure representing antenna losses. Losses such as radiation, conductivity, dielectric and surface wave are considered in the antenna design. Its mathematical expression can be written as follows:

$$\frac{1}{Q_t} = \frac{1}{Q_{rad}} + \frac{1}{Q_c} + \frac{1}{Q_d} + \frac{1}{Q_{sw}} \quad (2.7)$$

In this formula, Q_t represents the total quality factor, Q_{rad} represents the quality factor due to radiation losses, Q_c represents the quality factor due to conductivity losses, Q_d represents the quality factor due to dielectric losses, and Q_{sw} represents the quality factor due to surface wave losses. Surface wave losses are generally negligible in very thin surfaces ($h \ll \lambda_0$) because the losses are very low. For thicker substrates, where the substrate height is close to or equal to the wavelength, this loss must be considered. To eliminate this loss, special cavities or cavities can be created around the antenna to prevent surface waves from propagating. This method is important for thick substrates that are prone to surface wave losses [1][15].

For very thin substrates ($h \ll \lambda_0$), there are some mathematical approaches to calculate the quality factors due to different losses. These formulas are as follows:

$$Q_c = h\sqrt{\pi f \mu \sigma} \quad (2.8)$$

$$Q_d = \frac{1}{\tan \delta} \quad (2.9)$$

$$Q_{rad} = \frac{2\omega\epsilon_r}{\frac{hG_t}{l}} K \quad (2.10)$$

$\tan\delta$ in the quality factor (Q_d) formula due to dielectric losses represents the loss angle of the substrate material. Sigma (σ) represents the conductivity of the conductors associated with the patch and the ground plane, (G_t/l) represents the total conductivity per unit length of the radiation gap. We need a separate formula to calculate the constant K in the formula:

$$K = \frac{\iint_{area} |E|^2 dA}{\oint_{perimeter} |E|^2 dl} \quad (2.11)$$

In TM_{010}^x mode, for rectangular apertures:

$$K = \frac{L}{4} \quad (2.12)$$

$$G_t/l = \frac{G_{rad}}{W} \quad (2.13)$$

For very thin substrates the dominant factor, Q_{rad} , is inversely proportional to the height of the substrate. The standard fractional bandwidth is defined in terms of the total quality factor (Q_t) of the antenna. Its mathematical expression is:

$$\frac{\Delta f}{f_0} = \frac{1}{Q_t} \quad (2.14)$$

In this formula (Δf) is the bandwidth around the antenna's operating frequency. (f_0) is the antenna's design frequency. This formula does not consider the impedance matching at the antenna's input terminals. For this, there is a different mathematical method that expresses the fractional bandwidth by considering the VSWR (Voltage Wave Stop Ratio) value at the antenna's input terminals. The formula is as follows:

$$\frac{\Delta f}{f_0} = \frac{VSWR - 1}{Q_t \sqrt{VSWR}} \quad (2.15)$$

The bandwidth of a microstrip antenna is proportional to its volume, calculated from its area and height [33]. The mathematical expression that describes the relationship between them is as follows:

$$BW \sim \text{volume} = \text{area} \cdot \text{height} = \text{length} \cdot \text{width} \cdot \text{height} \sim \frac{1}{\sqrt{\epsilon_r}} \quad (2.16)$$

As can be understood from this statement, the bandwidth of the antenna is inversely proportional to the square root of the dielectric constant of the substrate. When a substrate with a lower dielectric constant is used, the bandwidth of the antenna increases [1][2][4][15].

In microstrip antennas, the input impedance consists of two main components. These are resonant resistance and reactance resistance. When the resonance resistance of the antenna at the resonance frequency is low, the antenna transfers energy easily to the transmission line. The feed reactance is affected by the position of the feed point of the antenna. When the feed point approaches one of the edges, the magnetic field strengthens and the reactance increases. The formula used to calculate the input impedance of a microstrip antenna is:

$$x_f = -\frac{\eta k h}{2\pi} \left(\ln \frac{k d}{4} + 0.577 \right) \quad (2.17)$$

In this formula, x_f is the feed reactance, k is the wave number, h is the height of the antenna, d is the diameter of the feed probe, and η is the internal impedance. This formula is used to calculate the input reactance depending on the physical dimensions of the antenna and the operating frequency [1][2][15]. If the reactance value is too high or too low, the performance of the antenna will be adversely affected. Impedance matching elements may need to be included in the design.

Another topic that needs to be addressed in microstrip antennas is “Coupling”. This topic is based on the principle of expressing the effect of one antenna element on another. Surface waves propagating on the dielectric material of the antenna create a kind of electromagnetic field around the antenna. In this case, surface waves can transfer energy between the antennas and strengthen the effect of one antenna on the

other [1][4]. In antenna arrays, connections can be formed between the antennas due to surface waves. The coupling effect varies depending on the position of the antenna elements relative to each other and the distance between them. When two microstrip patch antennas positioned parallel to each other along the E-plane are considered, the fields between the elements are in TM (transversal magnetic) mode. Since TM mode is more prone to surface wave excitation, it causes a stronger connection between the elements [2][6]. If these two patches were positioned parallel to each other along the H-plane, the field between the elements would be in TE (transversal electric) mode. In this case, there would be less coupling between the elements because there would be no strong dominant mode surface wave excitation [1][15]. In addition to this positioning, how close the patches are to each other and the frequency at which they operate also affect coupling [1][4].

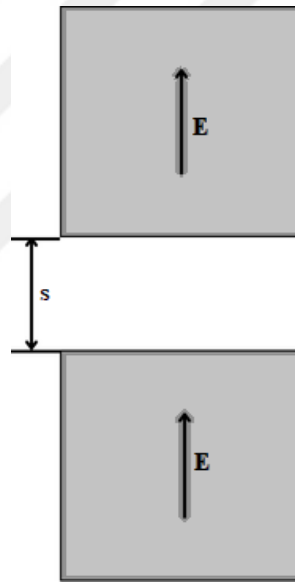


Figure 3: E-plane arrangements of microstrip patch antennas

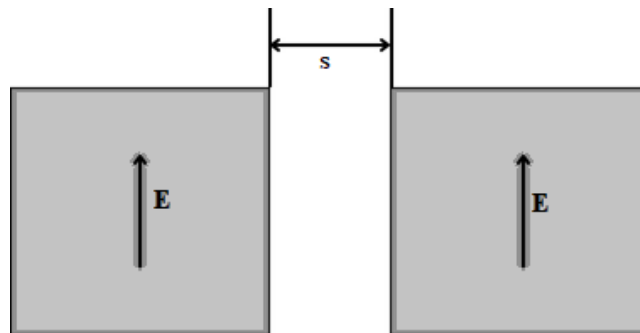


Figure 4: H-plane arrangements of microstrip patch antennas

In the E-plane, if the distance 's' shown in figure 3 and figure 4 is positioned at less than 10% of the free-space wavelength ($s < 0.10\lambda_0$), an optimized coupling isolation situation is achieved. For the H-plane, if the distance 's' is greater than 10% of the free-space wavelength ($s > 0.10\lambda_0$), the coupling effect is minimal [1][4][6].

The coupling formula for the E-plane is:

$$G_{12} = \frac{1}{\pi} \sqrt{\frac{\epsilon}{\mu}} \int_0^\pi \left[\frac{\sin(\frac{k_0 W}{2} \cos \theta)}{\cos \theta} \right]^2 \sin^3 \theta \left[2J_0\left(\frac{Y}{\lambda_0} 2\pi \sin \theta\right) + J_0\left(\frac{Y+L}{\lambda_0} 2\pi \sin \theta\right) + J_0\left(\frac{Y-L}{\lambda_0} 2\pi \sin \theta\right) \right] d\theta \quad (2.18)$$

The mutual conductance formula for the H-plane arrangement is:

$$G_{12} = \frac{2}{\pi} \sqrt{\frac{\epsilon}{\mu}} \int_0^\pi \left[\frac{\sin(\frac{k_0 W}{2} \cos \theta)}{\cos \theta} \right]^2 \sin^3 \theta \cos \left(\frac{Z}{\lambda_0} 2\pi \cos \theta \right) \left[1 + J_0\left(\frac{L}{\lambda_0} 2\pi \sin \theta\right) \right] d\theta \quad (2.19)$$

In these formulas, k_0 is the free space wave, W and L are the width and length of the antenna, λ_0 is the free space wavelength, Y and Z are the centre-to-centre separations between the patches, and J_0 is the zeroth order Bessel function [1][4][15].

2.3 ANALYSIS METHODS IN MICROSTRIP ANTENNAS

There are various methods used for the analysis of microstrip antennas. These methods are generally divided into two groups. The first group includes the transmission line model, the cavity model, and the modal expansion model. These three analysis methods are based on the equivalent current around the patch edges. In the second group, there are numerical methods such as Method of Moments (MoM), Finite Element Method (FEM), Spectral Domain Technique (SDT) and Finite Difference Method in Time Domain (FDTD). These analyses are based on the electric current distribution on the patch conductor and the ground plane [1][2][15].

The transmission line model is the simplest among the aforementioned analysis methods. Although it provides a physical perspective, its accuracy is low. In the transmission line model of microstrip antennas, the scattering effect occurs at the edges due to the limited patch size. The amount of scattering is related to the dimensions of the rectangular patch and the height of the substrate. This causes the physical dimensions of the patch to be perceived electrically as larger. The scattering effect generally decreases when the ratio of the length of the rectangular patch to the height of the substrate is greater than 1. This factor is an important parameter to be considered in the design phase since it affects the resonant frequency of the antenna [1][4].

The effective dielectric constant (ϵ_{reff}), which is a function of frequency, is defined to account for fringing and to explain wave propagation in the line. This constant is defined by assuming that the central conductor height above the ground plane and the original size of the microstrip line are embedded in a single dielectric material, allowing the electrical properties of the line, especially the propagation constant, to be assumed the same as those of the actual line. As the operating frequency increases, the electric field lines are seen to gather in the substrate such that the microstrip line behaves like a homogeneous line through the substrate, thus the effective dielectric constant approaches the dielectric constant of the substrate. Although the effective dielectric constant is constant at low frequencies, it monotonically increases at mid-frequencies, approaching the dielectric constant of the base material. The effective dielectric constant at low frequencies for initial static values can be calculated with the following formula:

$$\text{if } \frac{W}{h} > 1, \quad \epsilon_{\text{reff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + \frac{12h}{W} \right)^{-1/2} \quad (2.20)$$

The W/h ratio in the formula is the ratio of the width (W) of the rectangular microstrip antenna to the height (h) of the substrate. ϵ_r is the substrate dielectric constant [1][2].

As mentioned in previous chapters, the fringing effect causes the electrical dimensions of the antenna patch to appear larger than its physical dimensions. The mathematical expression for this extended length is as follows:

$$\frac{\Delta L}{h} = 0.412 \left(\frac{(\epsilon_{reff} + 0.3)(W/h + 0.264)}{(\epsilon_{reff} - 0.258)(W/h + 0.8)} \right) \quad (2.21)$$

In this formula, ΔL represents the extended length. Since the rectangular patch extends by ΔL on both sides, the total effective length can be mathematically expressed as:

$$L_{\text{eff}} = L + 2\Delta L \quad (2.22)$$

In the design process, the dielectric constant of the base material (ϵ_r), the height of the base (h) and the resonance frequency (f_r) of rectangular microstrip antennas are the parameters that need to be known. The parameters to be found are (W) and (L). In determining the antenna width (W), the speed of light in space (v_0) and the resonance frequency (f_r) are used. This formula is as follows:

$$W = \frac{\frac{v_0}{2f_r}}{\sqrt{\frac{\epsilon_r + 1}{2}}} \quad (2.23)$$

There is a formula for determining the actual length (L) of the patch using the resonance frequency and effective dielectric constant.

$$L = \frac{\frac{v_0}{2f_r}}{\sqrt{\epsilon_{\text{reff}}}} - 2\Delta L \quad (2.24)$$

The dimensions of the rectangular microstrip antenna can be adjusted to operate at a specific resonant frequency using these two formulas. The width and length of the antenna are parameters that directly affect the frequency response and radiation efficiency. For this reason, these parameters must be calculated accurately during the design process [1][2][4][15].

When the cavity analysis model is used, the fields within the dielectric substrate between the patch and the ground plane can be accurately calculated. This is because the microstrip antenna structure functions as an electrically charged void or cavity. In the cavity model, the dielectric substrate region is treated as being enclosed by perfect electrical conductors and perfect magnetic walls around the perimeter of the patch.

This model is an approximate model that theoretically has a reactive input impedance that does not radiate any power [1][2][6].

When the microstrip patch is energized, the attractive and repulsive charge distributions are seen on the top and bottom surfaces of the patch and also on the surface of the ground plane. To explain these two attractive and repulsive mechanisms, the attractive mechanism, which tries to maintain the charge concentration under the patch, interacts between the opposite charges under the patch and the ground plane, while the repulsive mechanism, which tends to push the charges from the edges of the patch to the top surface, interacts between similar charges on the bottom surface of the patch. The currents created by these two mechanisms are shown with their directions in Figure 5. The J_b current is a current formed on the bottom surface of the patch. J_t , on the other hand, occurs on the top surface of the patch. Since the height to width ratio is small in most microstrip antennas, it is observed that the attractive mechanism dominates, and accordingly the charge concentration and current flow remain under the patch. The current increase from the edge of the patch to the top surface decreases as this ratio decreases. In order to prevent the formation of tangential magnetic field components at the edges of the patch, the height to width ratio should theoretically approach zero. In this case, the side walls can be modelled as perfectly magnetic conductive walls without affecting the electric and magnetic field distributions at the bottom of the cavity [1][2][4][15].

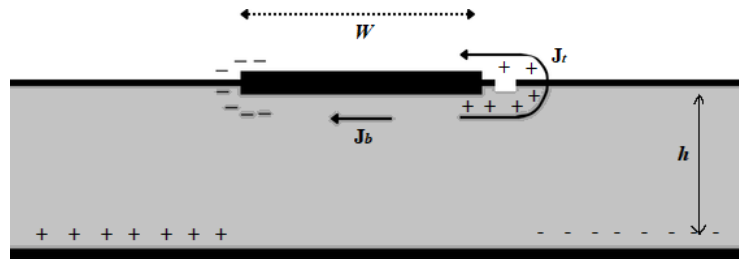


Figure 5: Charge distribution and current density creation on microstrip patch

In practice, considering a microstrip antenna only as a cavity would result in an antenna that cannot radiate and has a purely reactive input impedance, which would show only real poles in the impedance function. For more accurate analysis, radiation must be considered, and a loss mechanism must be defined. This requires the inclusion of radiation resistance R_r and dielectric loss resistance R_L , making the input impedance complex and the function having complex poles. Additionally, an effective loss

tangent δ_{eff} , which makes the microstrip antenna lossy using the cavity model, is defined. This is mathematically the inverse of the quality factor ($\delta_{\text{eff}}=1/Q$) [1][2][15].

The inefficiency of microstrip antennas is due to the fact that waves generated in the thin dielectric substrate only partly radiate when they reach the edge of the patch, creating reflections. The regions beneath the patch generate standing waves described by cosinusoidal wave functions. Given that the substrate height is very small ($h \approx \lambda$, where λ is the wavelength within the dielectric), the field variations along the height are regarded as constant, since the fringing fields at the patch edges are minimal. Within the cavity, only TM_x field configurations are considered [1][4].

The Modal Network Model (MNM) is an extension of the cavity model analysis of microstrip antennas discussed above. Additionally, it allows a more detailed examination of the electromagnetic fields beneath the patch. In terms of operating principles, the region between the patch and the ground plane is considered as magnetic walls and electric walls around the patch. The patch is analysed as a two-dimensional planar network with numerous ports, which are the points of interaction of electromagnetic fields around the patch. The multiport impedance matrix of the patch is obtained from the Green Function, which mathematically expresses the electromagnetic behaviour of a two-dimensional patch [1][6]. In order to account for the energy and radiation emitted from the edges of the patch, fringing fields and radiated fields around the patch are included in the model by adding an equivalent edge reception network.

The segmentation method encountered in MNM analysis is generally used in other complex analysis methods. In order to analyse electromagnetic interactions more easily, the patch is divided into small sections representing different parts. Then, the impedance of each section is calculated to create the overall impedance matrix of the patch. Calculating the electromagnetic interactions in different parts of the patch is important to understand how the patch creates a radiation pattern and the efficiency of the antenna. The calculated impedance matrix helps us analyse important features of the antenna such as radiation pattern, bandwidth and input impedance [1][2][15]. The voltage distribution on the antenna surface, which affects the radiation pattern of the antenna, provides detailed information about the electromagnetic field of the antenna, while the voltage around the patch provides details about the strength and direction of the electric field along the edges of the antenna. MNM is advantageous because it is simple and provides physical visibility. The voltage distribution on the antenna

surface, which affects the radiation pattern, provides detailed information about the electromagnetic field of the antenna, while the voltage around the patch details the strength and direction of the electric field along the edges of the antenna. MNM is advantageous because it is simple and provides physical insight. It also simplifies the calculation of radiation from the voltage distribution. Despite these advantages, this method is valid for regular patch geometries. Numerical techniques may be required for antennas with complex geometries [1][2][4][6].

Another analysis method is the method of moments (MoM). It generally describes the antenna with a mathematical equation based on the currents on the surface of microstrip antennas and the currents inside the dielectric material. It expresses the mathematical equation with an integral equation, considering the images of the unknown currents formed on the patches and feed lines on the ground plane. This integral equation is transformed into an algebraic equation. This method considers the fringing effect that affects the physical length of the antenna patch. In addition, it provides insight into the radiation pattern of the antenna and its performance [1][2][4].

The surface current integral formula used for this method is:

$$\int_S G(r, r') J(r') dS' = V(r) \quad (2.25)$$

$G(r, r')$, the Green's function, $J(r')$, the surface current density, and $V(r)$, the applied voltage.

Integral equation for the volume polarization current in the dielectric:

$$\int_V G(r, r') P(r') dV' = E(r) \quad (2.26)$$

$G(r, r')$, the Green's function, $P(r')$, the polarization density in the dielectric, and $E(r)$, the electric field.

Although these formulas are used to understand the electromagnetic behaviour of the antenna and calculate its properties such as radiation pattern, MoM analysis is usually a field that requires expertise. For detailed calculations, special software such as IE3D is used [6][15].

FEM (Finite Element Method), compared to the previous method, this method is suitable for volumetric structures. In this method, the structure to be analyzed is divided into small pieces called finite elements, which vary depending on the structure. These pieces can be countless finite surface or volume elements called finite elements. Since the patch is divided into many subregions in this analysis method, it involves integrating specific basis functions over each element. The wave equation is reduced to two boundary value problems with inhomogeneous boundary conditions representing cases where the boundary values in the system are not constant or regular. The first is the Laplace equation with inhomogeneous boundary conditions. The second is the inhomogeneous wave equation with homogeneous boundary conditions. Solving the problem by breaking it into simpler subproblems facilitates finding the overall solution [1][2][6].

Another analysis method is the Spectral Domain Technique (SDT), used for analysing electromagnetic structures such as microstrip antennas. To analyse the electromagnetic behaviour on the patch in the frequency domain, Fourier transform is applied in two perpendicular directions in the substrate plane along the conductive patch. In order to simulate the real boundaries of the antenna, boundary conditions are added to the Fourier transform plane. The current distribution on the conductive patch is expressed with certain basis functions and used to model this distribution. A matrix equation is created based on the current distribution and boundary conditions. By solving this matrix equation, the electric current distribution on the patch and the equivalent magnetic current distribution on the substrate surface are obtained. Finally, parameters such as the gain, bandwidth and radiation pattern of the antenna are analysed [1][4][6].

The FDTD (Finite Difference Time Domain) method is a numerical analysis method that calculates the changes in the analysis fields using finite differences in the time domain. It is used to model the patterns of microstrip antennas and simulates how the electric and magnetic fields change with time according to the material properties and physical structure. The first step is to create a time and space grid for the electric and magnetic fields. The E-fields are aligned with the boundaries of the configuration, while the H-fields are considered at the centre of each E-cell. Each cell contains the properties of the material within it. After the structures of the antenna are triggered with a suitable excitation function to ensure the propagation of electromagnetic waves, the time-dependent changes of the electric and magnetic fields are calculated at certain

points. In order to evaluate the performance, the voltage between two points is obtained by the integral of the electric field. In order to analyse the frequency response of the antenna, the current is calculated by the circumferential integral of the magnetic field around the conductor and then the Fourier transform is applied [1][2][15].

This numerical analysis provides a detailed understanding of the electric current distribution on the antenna surface. One of the advantages of this analysis is that it can yield highly accurate results for any antenna shape.



CHAPTER III

MULTIPLE BAND MICROSTRIP ANTENNA

3.1 MULTIBAND MICROSTRIP PATCH ANTENNAS

The primary reason for the need for multiband in microstrip antennas is the requirement for modern communication systems to operate across multiple frequency bands. Multiband microstrip antenna structures have evolved in parallel with the complex structure of modern telecommunication and communication systems. For user experience enhancement and increased versatility of devices, it is necessary for devices to operate on multiple frequencies. An example of this is a single antenna structure being compatible with different technologies such as GSM, LTE, and 5G, which operate in different bands [1][4][6].

The basic working principle of multiband microstrip antennas is based on the creation of more than one resonance frequency in the antenna structure. Each resonance frequency provides maximum performance of the antenna in a certain frequency band. Thus, more than one device or system can be operated from the same antenna. Performance increase is also observed. Using a single antenna reduces the cost and also reduces the size of the device. Multiple band microstrip antennas can be obtained using various methods. Using more than one resonator in different layers or in different positions on the same layer in the design of the antenna, using slot cutting, reactive loading, shorting posts and layered structures whose sizes and positions determine the resonance frequencies on the patch are a few of these methods. This subject is discussed in more detail in the following topics [1][2][15].

Today, the use of this antenna structure is very widespread. The application areas include mobile phones and mobile devices, WLAN, satellite communication, RFID, and military and defence applications [4][6].

3.2 DUAL-BAND MICROSTRIP ANTENNAS

Microstrip antennas are frequently used in various fields due to their high adaptability to different applications. As the range of use is broad, numerous

developments have been seen in terms of optimization in their design. Efforts to achieve dual-band microstrip antennas are among these developments. It is possible to develop these antennas to operate at fixed frequencies, tunable at one or both frequencies. Moreover, various configurations exist to achieve dual-band operation. This topic will be discussed under this heading [1][4][6].

Microstrip antennas that can operate at multiple frequencies corresponding to different resonance modes have characteristics that affect the performance of each resonance mode differently. Properties such as radiation pattern, polarization and input impedance may change in different modes. Therefore, different optimizations may be required according to system requirements. Dual-band MSA is a type of antenna that can operate at two different frequencies, either fixed or tunable. This feature can meet the needs for wide bandwidth [1][4][15].

To create a dual-band antenna system with a microstrip antenna, a single feed point or two separate feed points can be used, or the antenna design can be configured to make certain modes tunable in frequency. For example, one mode can remain fixed while the frequency of the other mode can be adjusted according to the user's needs [4][6][15].

An RMSA (rectangular microstrip antenna) that can operate in TM_{10} and TM_{30} modes can radiate with the same polarization at two different frequencies. In addition, the TM_{30} mode has approximately three times the resonant frequency of the fundamental mode, the TM_{10} mode, making the antenna more suitable for dual-band operation. Other types of microstrip antennas, CMSA and TMSA, can achieve dual-frequency performance by using higher order modes [1][2]. For CMSA, the resonant frequencies corresponding to the higher-order modes, which are multiples of the fundamental mode's resonant frequency, lie in a range determined by the roots of the derivative of the Bessel function of order n [6][15].

Referring to the relationship between the Bessel function and the microstrip antenna, in the analysis of a microstrip antenna, factors such as the geometry of the antenna and the propagation of electromagnetic waves can be modelled by Bessel functions. In antenna design, the roots of the derivative of the Bessel function determine the antenna's resonant frequencies. The higher-order modes, which are multiples of the fundamental mode's resonant frequency, enable the antenna to operate at more than one frequency. This is part of the optimization of the design of a dual-band or multi-band microstrip antenna. The Bessel function is expressed as:

$$J_n(x) = \sum_{m=0}^{\infty} \frac{(-1)^m}{m! \Gamma(m+n+1)} \left(\frac{x}{2}\right)^{2m+n} \quad (3.1)$$

In this formula, n is the sequence number, and the gamma function is also included in the formula [1][6].

In applications requiring orthogonal polarization at two different frequencies, the length and width of the RMSA can be adjusted according to the frequency ratio and operated in TM_{10} and TM_{01} modes. Two orthogonal modes are obtained with a single feed point [1][4].

Instead of coaxial feed, an aperture-coupled RMSA design can be considered. By adding an inclined slot to the ground plane in this design, impedance matching can be achieved at two frequencies. To increase the efficiency of communication systems, dual-frequency band operation can be achieved in an elliptical MSA using two orthogonal feed points [2][6].

Another method for achieving dual-band operation in MSAs is stub-loaded loading. This technique can be implemented by adding a short-circuited coaxial line segment to an RMSA type antenna. The length of the coaxial line allows the adjustment of the two frequencies. Instead of a coaxial line, a short-circuited microstrip line etched on a substrate with a length of half the wavelength can be used. Alternative methods, such as changing the short-circuiting distance of the microstrip line or creating a cavity on the antenna, affect the distance between the two resonant frequencies. This segment is equivalent to a short-circuited half-wavelength element. The change in the length of the segment is important for frequency tuning. Consequently, dual-band microstrip antennas (MSA) can be obtained by adding a single or double open-circuited quarter-wavelength element [1][4][15].

In order to understand how the antenna can be tuned and optimized for dual band operations, the experiment was carried out, where the single stub loaded RMSA, the dual frequency was obtained at 2.434 GHz and 3.377 GHz, respectively ($L = 3$, $W = 4$ cm, $\epsilon_r = 2.55$, $h = 0.159$ cm, $\tan \delta = 0.00$, feed at $x = 0.8$ cm and the stub dimensions $l = 1.5$ cm and $w = 0.4$ cm) [2]. The bandwidths were calculated as 26 MHz and 35 MHz, respectively. The stub length was varied to tune both frequencies and the results were tabulated in the figure 6 [2][6][15]:

Stub Length / (cm)	f_1 (GHz)	f_2 (GHz)	f_2/f_1
1.4	2.508	3.443	1.37
1.5	2.434	3.377	1.39
1.6	2.361	3.324	1.41
1.8	2.214	3.245	1.47
2.0	2.074	3.188	1.54

Figure 6: Stub and frequency [15]

As can be seen from this table, as the length of the stub increases from 1.4 cm to 2.0 cm, both resonance frequencies decrease and the f_2/f_1 ratio changes from 1.37 to 1.54 [15].

A single-stub RMSA with an asymmetric structure has a high level of cross-polarization. Placing an open-circuit quarter-wavelength stub on both sides of the radiation edges of the rectangular patch will make the structure symmetrical [15].

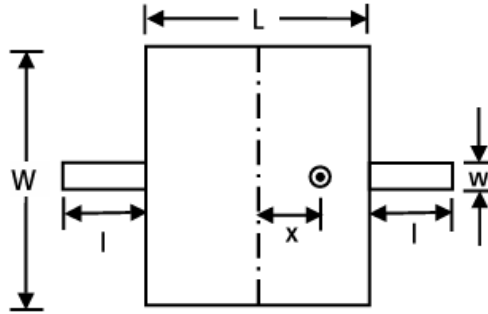


Figure 7: RMSA with two stubs [15]

In the antenna design shown in Figure 7, for a length of l is 1.5 cm and a distance of x is 0.6 cm, dual frequency was obtained at frequencies of 2.243 GHz and 3.603 GHz. By changing the length of the stub, namely the value of l , the ratio of the two frequencies can be adjusted, and triple-frequency response can be obtained when unequal stub lengths are designed [2][15].

The Notch-Loaded microstrip antenna design, which is obtained by cutting a notch or adding spur line to one side of the antenna, is an alternative method used to obtain dual-band operation. This design has a similar effect to the stub-loaded method. In addition, it reduces the size of the antenna [1][6][15].

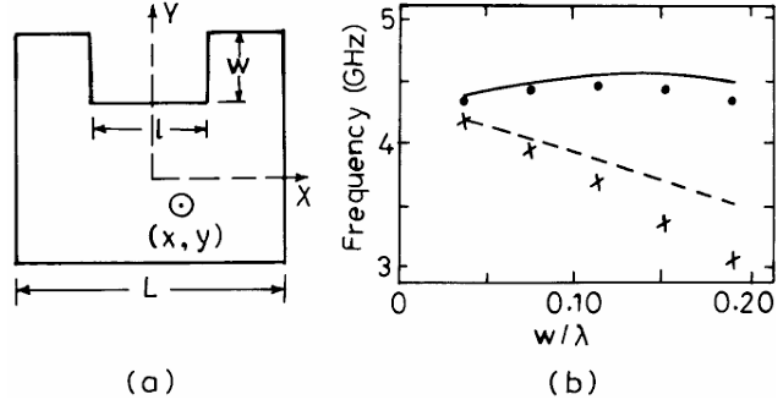


Figure 8: (a) Square MSA with a notch (b) variation of resonance frequencies [15]

As an example, explaining through a square-shaped MSA, the design involves creating a rectangular notch with a depth of w on the non-radiating edge of this antenna. In the design shown in Figure 8(a), the patch side length (L) is 2.5 cm, notch length (l) is 1.0 cm, dielectric constant (ϵ_r) is 1.79, height (h) is 0.08 cm, and loss tangent ($\tan \delta$) is 3.2×10^{-4} . When set to be equal in the x and y coordinates ($x=y=0.523$) and fed along the diagonal with a 50- Ω coaxial line, the resonance frequency for the notchless square patch ($w=0$) was observed to be 4.3 GHz. The resonance frequencies f_1 and f_2 change with the increase of notch width (w). Since the change at frequency f_1 is more significant compared to f_2 , orthogonal polarization increases [1][4][15].

When the above-mentioned methods are tried, it is observed that the frequency ratio (f_2/f_1) is less than 2. To achieve this ratio greater than 2, various short-circuit configurations can be used. Short-circuit poles can be a suitable choice for this method. The principle of this method is based on changing the resonant frequency of only one particular mode of the antenna. It does this by selectively changing the current distribution. For example, in an RMSA system operating in TM_{10} and TM_{30} modes with the same polarization at both frequencies, a short-circuit pole placed at the zero point of the TM_{30} mode will not change the corresponding resonant frequency but will significantly affect the TM_{10} mode frequency [2][6].

In order to achieve dual-band operation, two lumped capacitors can be used instead of short-circuit poles. These capacitors can be constructed using reverse-bias varactor diodes. These diodes allow the antenna to operate at different frequencies by changing its electrical length. The antenna is fed with a microstrip line and dual stub impedance matching network to improve the input impedance. For example, the

dimensions of the antenna (L and W) are calculated for the high frequency $f_2 = 2.1\text{GHz}$. The dielectric constant (ϵ_r) and the thickness (h) are chosen as 4.4 and $h = 0.079\text{ cm}$, respectively. To reduce the effect of cross-polarization, varactor diodes are placed symmetrically at positions $0.3L$ and $0.7L$. As the reverse-bias voltage applied to the varactor diodes increases, the low frequency f_1 can be adjusted from 375 MHz to 650 MHz. This result allows the antenna to operate at different frequencies. Observing this design, it is seen that by adding varactor diodes, a dual-band microstrip with frequency adjustment is obtained [1][2][4][6][15].

To achieve dual-band performance, microstrip antennas can be reactively loaded by creating slots in the patch part of the antennas. Additionally, a combination of slots and short-circuiting can be added to this design. For example, an RMSA with a square slot in the centre lowers the resonance frequency by extending the surface current path. A feed point along the diagonal creates a dual-band with orthogonal polarization. Increasing the slot length will cause a decrease in both resonance frequencies. In an antenna system with different slot lengths, the position of the feed point is optimized [1][6].

Dual band can be achieved by creating slots on the antenna patch. To optimize this dual band performance, the resonant frequencies can be tuned by changing the parameters such as the width of the slots and the angle of the bent slots. The dimensions and positions of the slots can be adjusted to achieve the same polarization radiation pattern at two different frequencies and to change the ratio between the two frequencies. In this method, short-circuiting at the vertical central axis corresponding to the zero potential plane for TM_{10} and TM_{30} modes will reduce the antenna size by half [2][4][6].

Multiple resonators can also be included in the design to achieve dual-band operation. Multiple resonators that allow the antenna to resonate at different frequencies can be placed on the same plane (coplanar) or stacked planes. When the resonators are compact, the combined dual-band configuration will also be compact. Thus, the size of the antenna will be reduced while maintaining its dual-band feature [1][4].

When two rectangular patch antennas are placed close to each other, they are electromagnetically coupled through the gap between them. This coupling is called “gap-coupled.” The proximity of the two rectangles strengthens this coupling. As a result, the size of this gap changes the frequency response of the antenna. The upper

resonant frequency of the antenna increases with increasing gap. The lower resonant frequency of the antenna decreases due to the increasing series gap capacitance. In summary, the separation between the two resonant frequencies increases, converting wide-band operation into dual-band operation [1][4][6]. There is also an alternative to this method to achieve dual band, the hybrid-coupled compact short-circuits RMSA design. In this design, there is a short-circuit pole in the centre of both patches. The coupling increased by placing a copper strip over the gap is called hybrid coupling. More specifically, hybrid coupling is the connection achieved through both the gap and direct contact. This connection results in dual-band response [15]. Additionally, designs for dual-frequency MSAs operating at S-band and X-band frequencies are available for radar and communication systems requiring a large separation between two frequencies. This design is shown in the figure 9:

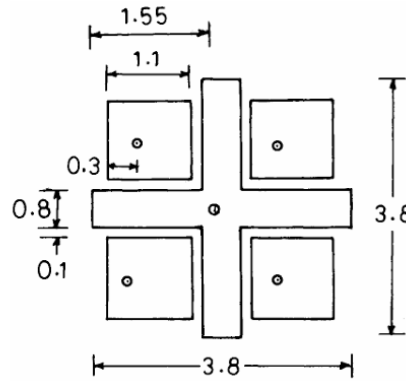


Figure 9: Dual frequency MSA at the S- and X-bands [15]

Cross patch operates in the S-band, while four square patches function as a sub-array in the X-band. Because the radiation edges of the cross patch are away from the four-square patches, adding the four-square patches causes a slight change in the resonance frequency. The resonance frequency of the four-square patches is more affected by the presence of the cross patch as it introduces an additional reactive load. The cross patch alters the electric field around the square patches, lowering their resonance frequency. In summary, using different elements like cross patches and square patches in antenna design allows for dual-band operation, as each patch resonates at different frequencies [15].

The methods mentioned above are some of the common techniques used to achieve dual-band microstrip antennas. In summary, these antennas can have their resonance frequency adjusted within a range of approximately 20% by loading MSAs

with external reactive components such as stubs, shorting posts, and varactor or PIN diodes [1][4][15]. Additionally, the air gap thickness between the patch substrate and the ground plane can be varied for adjustment. Adding slots to the antenna can reduce the distance between two resonance frequencies. Lower dual-frequency ratios can be obtained using a single short-circuited Rectangular Microstrip Antenna (RMSA) or Circular Microstrip Antenna (CMSA), while higher dual-frequency ratios can be achieved using a Single Mode Microstrip Antenna (TMSA) [1][2][6]. Dual-band performance developed for versatile use in communication systems means that the antenna can provide the same (or orthogonal) polarizations at both frequencies. The stacked geometry is an antenna design created by placing two or more antenna layers on top of each other. Resonances at different frequencies can be achieved by adding an air gap to the design of these antennas operating in the same mode. Another design showcasing multiple frequency performance is two parallel dipole antennas in the same plane, known as Aperture-Coupled Coplanar Parallel Dipoles [15]. All these designs are among the methods developed to meet the multiband requirement in microstrip antennas.

3.3 TRIPLE-BAND MICROSTRIP ANTENNAS

With the rapid development of wireless communication technologies, the need for antennas capable of operating in multiple frequency bands has emerged. Consequently, antennas that are small in size, lightweight, and capable of accommodating the working frequencies of multiple devices have gained attention. This is where the optimization of microstrip antennas according to these needs comes into play. In this context, the capability of microstrip antennas to operate in three different bands is an ideal option for these requirements. Triple-band microstrip antennas are suitable for supporting the multi-service needs of a single device that supports multiple communication protocols, saving space, and reducing costs by using a single antenna instead of multiple antennas [34]. For example, a triple-band MSA used in satellite communication systems can perform both uplink and downlink operations at different frequency bands with a single antenna. They are generally preferred in application areas such as mobile communication, satellite communication, Wi-Fi, WiMAX, and WLAN due to their advantages. A triple-band antenna can provide Wi-Fi at the 2.4 GHz band, WiMAX at the 5 GHz band, and satellite communication at the 7 GHz band. Additionally, triple-band antennas enable high-

speed data transfer by operating at multiple frequencies simultaneously. This feature provides a significant advantage in applications requiring broadband, such as video conferencing, live broadcasting, and high-speed internet connections. Another advantage of these antennas is their low power consumption [34]. They provide high performance with low power consumption. This advantage is often required in the mobile device sector to extend the battery life of mobile devices. Thus, as the energy consumption requirement decreases, it becomes a prominent antenna structure in terms of environmental sustainability. The antenna shows high adaptability according to usage area requirements. To explain this a bit more, a triple-band antenna used in satellite communication can receive signals from different satellites and simultaneously send data to different ground stations [34]. Similarly, a triple-band mobile antenna can operate in both the 4G LTE band and the 5G NR band. Although the usage areas of these antennas are quite broad as mentioned above, to summarize this topic a bit more, the common application areas are mobile communication, satellite communication, Wi-Fi/WLAN, and WiMAX. In the field of mobile communication, triple-band microstrip antennas support 4G LTE, 5G NR, GSM, and other mobile communication protocols. They are preferred in the field of satellite communication due to their ability to perform uplink (data transmission from a ground station or a user device to a satellite or a central receiver) and downlink (data transmission from a satellite or a central receiver to a ground station or user device) operations simultaneously. They are used in Wi-Fi/WLAN applications because they provide flexibility to operate in the 2.4 GHz, 5 GHz, and 6 GHz bands. They are used in WiMAX (Worldwide Interoperability for Microwave Access) systems because they provide broadband wireless access in the 2.5 GHz, 3.5 GHz, and 5.8 GHz bands [1][4][6].

Alongside these advantages, there are also some disadvantages of triple-band microstrip antennas. The design process of triple-band microstrip antennas is more complex compared to single-band antennas. This is because many parameters such as antenna dimensions, patch shapes, slots, and Defected Ground Structures (DGS) need to be arranged to operate the antenna at three different frequencies, and the presence of more components and details in the resonators complicates the design [1][2][35]. Additionally, ensuring correct resonance for each frequency band complicates the design further. Achieving proper impedance matching is another challenge due to the need for different impedance values for each frequency band [4]. Complex impedance

matching techniques may be required. If adequate impedance matching is not achieved, the efficiency and performance of the antenna decrease [6]. Another disadvantage is that the complexity of the triple-band antenna structure leads to larger sizes and assembly difficulties. More components increase the size and weight of the antenna. Its complex structure requires more precision during assembly [15][35].

A microstrip antenna may have multiple patches in its design to operate at three different resonant frequencies. Each patch in the design is optimized to resonate [35]. This optimization process usually involves sizing the patch, attaching it to the correct location, and impedance matching [1]. The design and performance principles of triple-band microstrip antennas are based on electromagnetic theory and Maxwell's equations. Therefore, some theories need to be addressed to analyse the operating principles of these antennas [1]. One of these is Gauss's Law for Electricity ($\nabla \cdot E = \frac{\epsilon}{\rho}$). Since it is important to analyse the distribution of the electric field for each patch to resonate at a specific frequency in triple-band microstrip antennas, this law, which explains the distribution of the electric field in the presence of electric charges, is used to determine how the electric field is distributed along the patch in microstrip antennas [3]. More specifically, Gauss's electric law analyses the electric field intensity on the surface of each patch. The distribution of the electric field and the resonant frequencies are determined by the size and shape of the patch. Three different patches are designed to achieve optimum performance at three different frequencies [4]. Another law that should be mentioned under this topic is Gauss's Magnetic Law ($\nabla \cdot B = 0$). The distribution of magnetic fields has an effect on the microstrip antennas and their resonant frequencies. Three different patches with different magnetic field distributions can operate at three different frequencies. The distribution of the magnetic field is influenced by the placement of the patches, which is why an optimization process may be necessary during the antenna design phase. Faraday's Law of Induction ($\nabla \times E = -\frac{\partial B}{\partial t}$) is another law that helps us understand and analyse the operating principles of triple-band microstrip antennas. This law helps us analyse the interaction of changing magnetic fields with electric fields in microstrip antennas. The operation of each patch in a triple-band microstrip antenna at a different frequency is made possible by this interaction. Another law to be addressed in this context is the Ampere-Maxwell Law ($\nabla \times B = \mu J + \mu\epsilon \frac{\partial E}{\partial t}$). This law, which explains the relationship between currents flowing along the patch and the magnetic fields they create when

each resonator operates at a specific frequency in triple-band microstrip antennas, is used to calculate the currents and magnetic fields. Additionally, since the current distribution and magnetic field relationship is important for impedance matching with the feed line of the antenna, it is also used for impedance matching [2][4][6].

When the recent articles are examined, it is seen that various processes have been tried to obtain triple band microstrip antenna. A brief summary of some of these recent articles will help to understand the subject.

In one article, a triple-band structure was achieved by adding notches and slots to the design of a rectangular microstrip antenna, allowing the antenna to resonate at 1.422 GHz, 1.791 GHz, and 2.467 GHz. [16]

When we examine another article, it is seen that the research on triple band provides high efficiency and low input impedance. The author of the article observed that the antenna exhibits stable performance in three different frequency bands (900 MHz, 1.8 GHz and 2.6 GHz). He suggested that these features would make the antenna a suitable option for mobile communication and fixed wireless applications. This article is also among the examples of triple band antenna design. [17]

When we look at a different study, we see the performance features of the triple-band microstrip antenna designed for WLAN/WiMAX applications, such as wide bandwidth and high gain (Smith et al., 2020). In this study, the focus was generally on the optimization of the antenna design and the ability to adapt to different bands. As a result, high performance was achieved in three different frequency bands (2.4 GHz, 3.5 GHz and 5.5 GHz) [18]. This article can be counted among the studies that prove that triple-band microstrip antennas are a suitable choice for versatile application.

CHAPTER IV

DESIGN AND ANALYSIS OF A TRIPLEBAND MICRISTRIP ANTENNA

4.1 A TRI-BAND ANTENNA DESIGN PRINCIPLE

In the previous chapters, we discussed the structure, working principles, general concepts, and other characteristics of microstrip antennas. Additionally, we examined methods and analyses on how to meet the multiband requirement in microstrip antennas. In this section, I will explain in detail my innovative design of a microstrip antenna with three-band function. To summarize, MSA is obtained by integrating a metal patch on an insulating layer. The operating principle of the tri-band antenna is based on the resonance of different patches of the antenna at three frequencies [1].

In this study, there are three different patches in the structure of the designed antenna. Each of these patches resonates at a different frequency. The main factor that determines the frequency of the patches is the physical size of the patch. This is explained in detail under the following headings. The dimensions of the patches in the design of this antenna have been calculated and optimized. The first patch is set to resonate at a frequency of 1.55 GHz, the second patch at a frequency of 2.0 GHz, and the third patch at a frequency of 2.92 GHz. Another striking feature in the design is that when the size of each patch is changed, it has a minimal effect on the resonance frequencies of the other patches. This can also be explained by the fact that the change in the length of a patch only changes the resonant frequency of that patch without significantly affecting the performance in the other bands of the antenna [2]. Thus, each frequency band in the designed antenna can be tuned independently. For usage area, when the size of this designed antenna is reduced by 1.13, the first and second frequency bands support 5G applications, while the third frequency band supports GPS applications. In particular, the 5G FDD (700-900 MHz) band and the GPS L2 (1.215-1.239) GHz band are the frequency ranges that this antenna can support simultaneously. With this feature, an efficient antenna design that offers multi-band support for 5G and GPS technologies is achieved.

4.2 GEOMETRY AND CONFIGURATION OF THE MICROSTRIP ANTENNA

Under this heading, the geometry and configuration of the designed triple band microstrip antenna are given. The geometry and dimensions of the antenna are given in the table and figure below. The antenna is designed on Rogers RT5880 dielectric substrate with a dielectric constant (ϵ_r) of 2.2. The loss tangent is 0.009 and the height is 1.6 mm. Since the dielectric constant will directly affect the resonant frequencies and bandwidths of the antenna, the selection of this material is important in the design. Copper tape with high electrical conductivity was selected as the patch material of the antenna (5.8×10^8 S/m) [1]. Copper is a preferred material in microstrip antenna designs due to its excellent electrical conductivity [15]. The width and length of the antenna are defined by the dimensions of the patch (W_p and L_p) and the ground (W_g and L_g) in the figure 10.

Table 1: Geometric Lengths of Microstrip Antenna

Parameter	Value (mm)
W_g	60
W_p	40
L_g	80
L_p	60
bY	10
dY	16

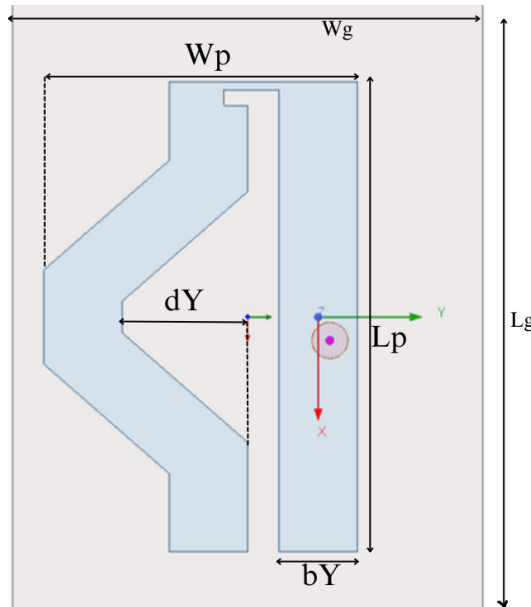


Figure 10: Dimensions of the Microstrip Antenna

The dimensions of the patch directly affect the resonant frequency. To determine the dominant mode of the antenna design, the mode with the lowest resonant frequency is calculated as the dominant mode. In microstrip antennas, it is observed that ($h \ll L$) and ($h \ll W$). When ($L > W > h$), the mode with the lowest frequency is the dominant mode, which is the TM_{010} mode. This mode indicates that the field changes by half a wavelength along the length and is constant along the width. The formula that helps us understand the relationship between the patch length and the resonant frequency in this case is as follows:

$$f_r = \frac{c}{2L\sqrt{\epsilon_e}} \quad (4.1)$$

In this formula, f_r is the resonant frequency (Hz), c is the speed of light (3×10^8 m/s), L is the length of the patch (m), ϵ_e is the effective dielectric constant [1].

This formula shows that the resonant frequency of the microstrip antenna is dependent on the patch length and the dielectric constant of the substrate [2].

To calculate the effective dielectric constant, the relative dielectric constant is used, and the formula is as follows:

$$\epsilon_e = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left[1 + \frac{10h}{W} \right]^{-1/2} \quad (4.2)$$

By applying this formula, the effective dielectric constant is calculated as:

$$\epsilon_e = \frac{2.2 + 1}{2} + \frac{2.2 - 1}{2} \left[1 + \frac{10 \times 0.016}{0.04} \right]^{-1/2} = 1.87 \quad (4.3)$$

Theoretical calculation of lengths in design:

- For the first resonance frequency (f_{r1}) = 1.55 GHz

$$L_1 = \frac{3 \times 10^8}{2 \times 1.55 \times 10^9 \times \sqrt{1.87}} = 70.76 \text{ mm} \quad (4.4)$$

- For the second resonance frequency (f_{r2}) = 2.00 GHz

$$L_2 = \frac{3 \times 10^8}{2 \times 2.00 \times 10^9 \times \sqrt{1.87}} = 54.85mm \quad (4.5)$$

- For the third resonance frequency (f_{r3}) = 2.92 GHz

$$L_3 = \frac{3 \times 10^8}{2 \times 2.92 \times 10^9 \times \sqrt{1.87}} = 37.57mm \quad (4.6)$$

The TM_{010} mode shown in Figure 11-(a) is the fundamental mode in a rectangular microstrip patch antenna. In this mode, the electric field lines, which are generally zero at the centre of the length, are concentrated along the long edges of the patch [1]. Based on this explanation, the electric field analysis performed at 1.55 GHz frequency in the HFSS program is shown in the figure 12. When this analysis is examined, the effective length at this frequency is indicated by the red line. More specifically, it can be observed that at the ends of this indicated red line in the figure 13, the electric field vectors are opposite to each other, and at the midpoint, the electric field is zero. This length, considering Table 1, is 74 mm. This value is very close to the 'Length' value calculated for the first resonant frequency.

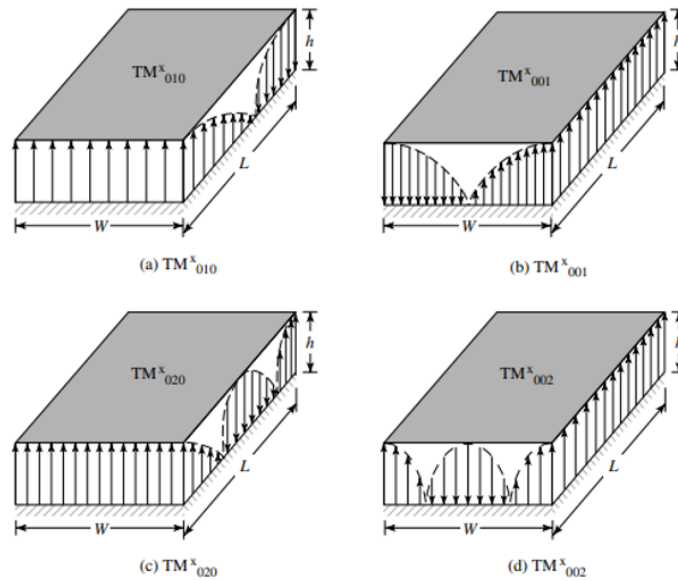


Figure 11: Field configurations (modes) for rectangular microstrip patch [1]

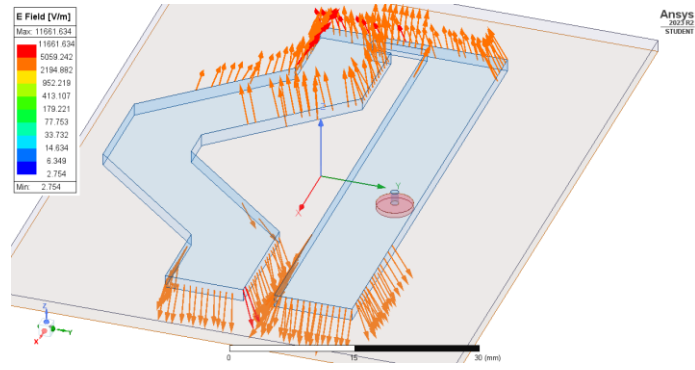


Figure 12: E-Field Analyses at 1.55 GHz on the Antenna Patch

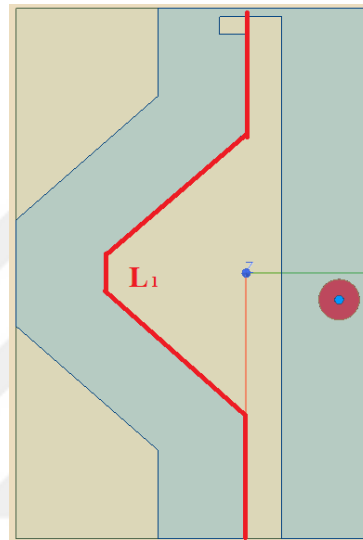


Figure 13: Corresponding Length of E-Field Analyses at 1.55 GHz (L_1)

Similarly, the electric field analysis performed at 2.00 GHz frequency in the HFSS program is shown in Figure 14. This section also exhibits the same characteristics as Balanis's TM_{010} mode. When this analysis is examined, it can be seen that at the 2.00 GHz frequency, the length represented by the red line marked on the designed image in the figure 15 of the antenna in the program is effective. This length is 60 mm, and similarly, it is found to be close to the theoretically calculated length for 2.00 GHz.

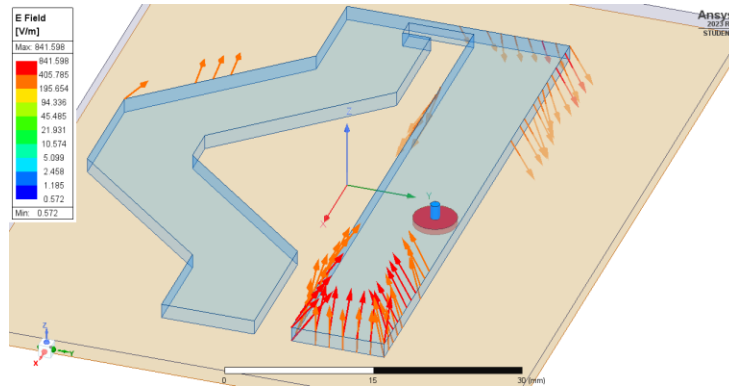


Figure 14: E-Field Analyses at 2.00 GHz on the Antenna Patch

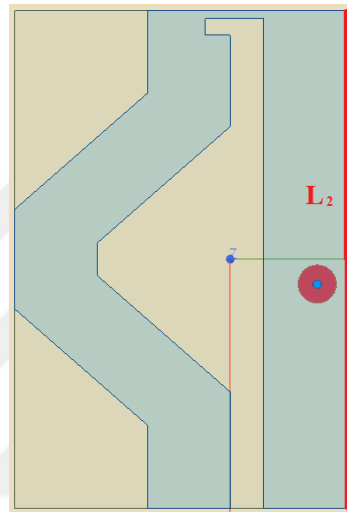


Figure 15: Corresponding Length of E-Field Analyses at 2.00 GHz (L_2)

When examining the electric field analysis for the 2.90 GHz frequency in the Figure 16, we again see that the length marked by the red line in the figure 17 is effective. This length is 33 mm and matches the theoretically calculated length for the third resonance frequency.

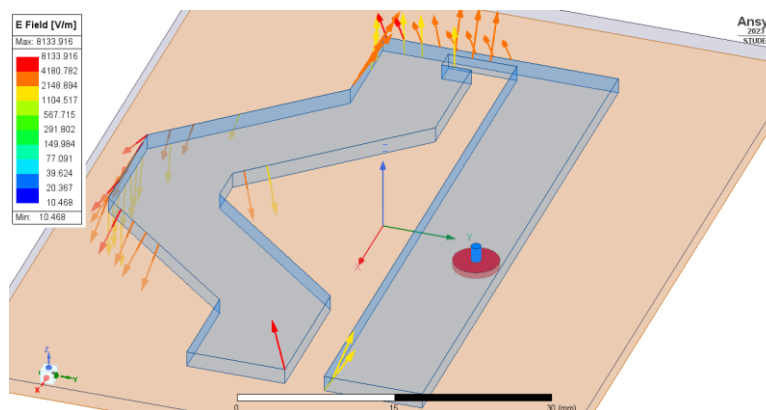


Figure 16: E-Field Analyses at 2.92 GHz on the Antenna Patch

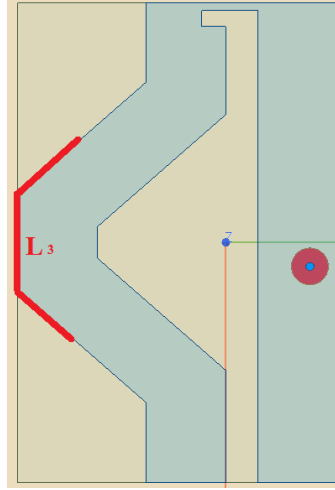


Figure 17: Corresponding Length of E-Field Analyses at 2.92 GHz (L_3)

The fringing effect mentioned in the previous chapter can create a difference between theoretical and practical length. Therefore, considering the fringing effect in the design implementation can help achieve better results [1].

The fringing effect mentioned in the previous chapter can create a difference between theoretical and practical length. Therefore, considering the fringing effect in the design implementation can help achieve better results.

In multiband microstrip antennas, in some cases, patch-to-patch interaction can affect performance. The close distance between patches causes electromagnetic fields to interfere with each other, while at the same time, this interaction affects the impedance characteristics of the antenna and thus its matching and efficiency. Another situation that negatively affects bandwidth and gain is the energy transfer of surface waves due to the decrease in the patch-to-patch distance [1]. Therefore, the bY and dY distances are adjusted to minimize patch-to-patch interaction, considering theoretical analyses.

4.3 PARAMETRIC ANALYSIS AND HFSS SIMULATION

Ansys HFSS program was used to design the antenna. After the theoretical calculations of the antenna, its design was made in this program. Figure 18 shows the design of the antenna on the program and also provides information about the port setting configuration. The detailed image of the antenna designed in the program is shown in Figure 10. The port is the structure that provides the electromagnetic signal to the antenna. As seen in the simulation design, the name of the port is determined as "Coax_Inner_Cond_T1". Port number '1' is the only port in the design. The determined

renormalizing Impedance is set to 50 ohms which is used in RF (Radio Frequency) applications. Impedance is an important parameter for the power transfer of the antenna. It should also be considered to minimize reflections. This impedance definition includes the resistance and reactive component of the impedance. Resistance allows us to evaluate the power transfer performance of the circuit. Reactance allows us to understand the response of the circuit depending on the frequency. The "i" in the explanation section in the table represents the phase angle of the reactive component.

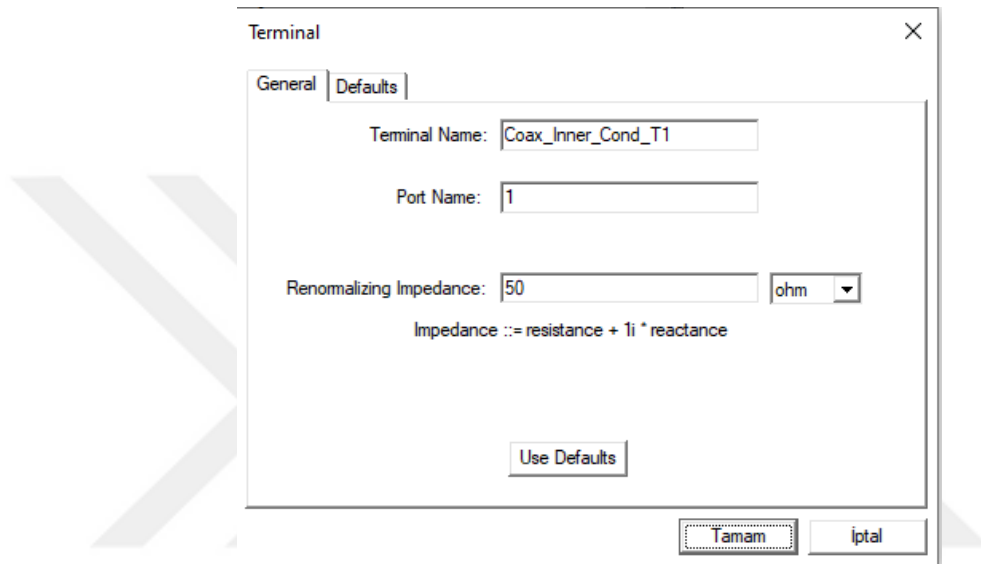


Figure 18: Port Setting Configuration

As seen in the “driven solution setup” Figure 19, during the simulation, the antenna was analysed at three bands of 1.55 GHz, 2.00 GHz and 2.92 GHz. These frequencies allow the antenna to operate effectively in more than one frequency band. The delta S value of 0.02 is the acceptable error margin at each frequency. The maximum number of transitions that determine the number of iterations was selected as 10. The number of iterations is important for producing accurate results.

Driven Solution Setup

General | Options | Advanced | Expression Cache | Derivatives | Defaults

Setup Name:

☒ Enabled ☐ Solve Ports Only

Adaptive Solutions

Solution Frequency: ☐ Single ☒ Multi-Frequencies ☐ Broadband

Frequency	Unit	Max. Delta S
1.55	GHz	0.02
2	GHz	0.02
2.92	GHz	0.02

Add Remove

Maximum Number of Passes:

Use Defaults

Figure 19: Driven Solution Setup

Subsequently, a plot was created showing the $|S_{11}|$ reflection coefficients of the designed antenna at its operating frequencies. This plot is shown in Figure 20. The interpretation of this graph is as follows:

- At 1.55 GHz, the antenna's $|S_{11}|$ reflection coefficient was measured at -13.90 dB. It is observed that this measured value is -13.15 dB, indicating that the reflection coefficient at this frequency is smaller than the accepted standard value of -10 dB [1]. In simpler terms, it shows that the antenna transmits most of the received power without reflection.
- At 2.00 GHz, the antenna's $|S_{11}|$ reflection coefficient was recorded as -14.40 dB. This value is below the accepted standard value.
- At 2.92 GHz, the reflection coefficient of the antenna $|S_{11}|$ was measured as -14.03 dB. This is the band where the best impedance matching is observed. This means that the signal loss is low.

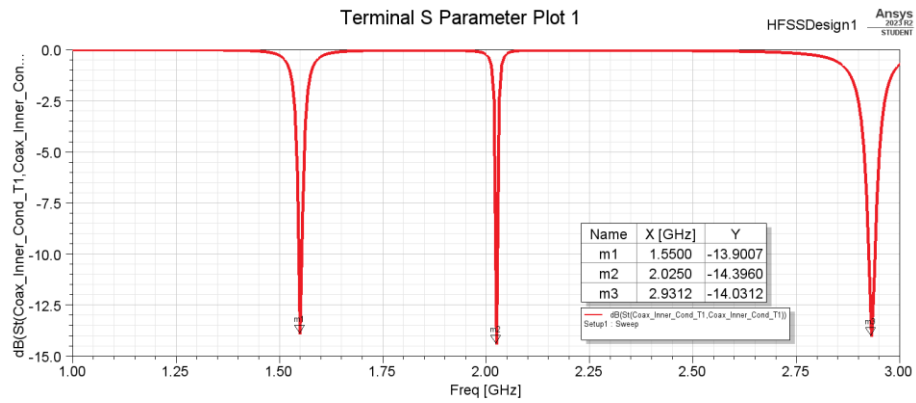


Figure 20: S11 Parameter of Tri-Band Microstrip Antenna

The $|S_{11}|$ parameter analysis performed to clearly explain the effect of the bY length on the second resonance frequency is shown in the figure 21. This analysis was conducted by incrementally increasing the bY length from 6 mm to 11 mm in 1 mm intervals. When the length is changed between these values, it is seen that the first and third resonances do not change, but the second resonance exhibits a variable band performance between 2 GHz and 2.13 GHz. More precisely, in the triple-band microstrip antenna design, the bY length significantly affects the second resonance frequency, but does not affect the first and third resonance frequencies. When this result is evaluated, the designed antenna shows constant performance in certain frequency bands, while adjustments can be made in the second frequency band.

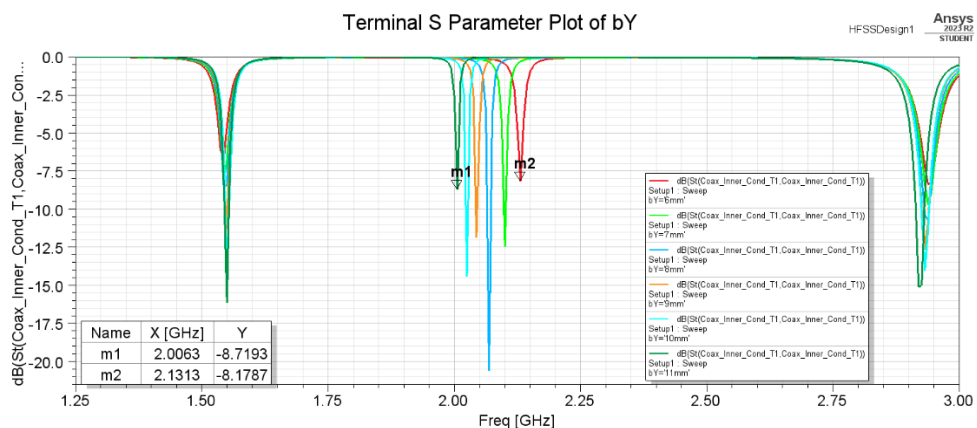


Figure 21: S11 Parametric Result of bY Length

Similarly, while all other lengths of the antenna design are fixed, the $|S_{11}|$ value of the dY length is shown in Figure 22 as the change of six values between 11 mm and

16 mm parametrically. In this graph, the change of the second and third resonance frequencies is very little, while the change of the first resonance is 1125 MHz.

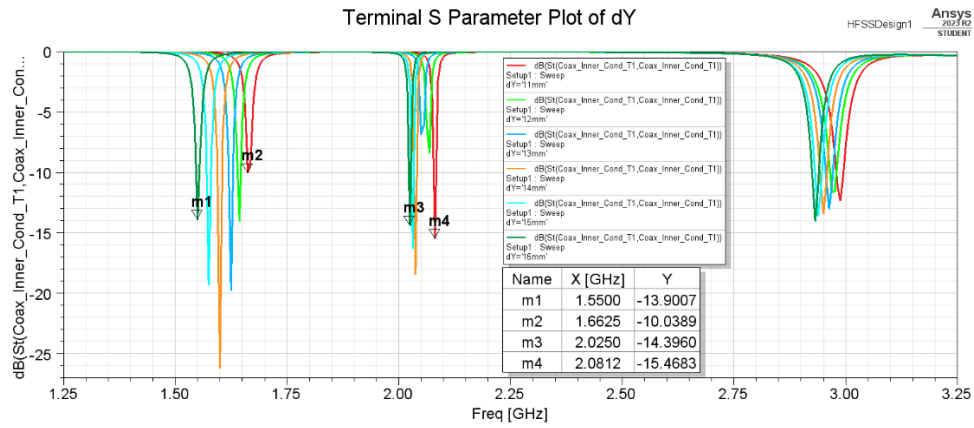


Figure 22: $|S_{11}|$ Parametric Result of dY Length

With the feature seen in these two graphs, precise adjustments can be made to the desired frequency band in the antenna design. For example, when it is necessary to work in a certain frequency band in a communication system, frequency compatibility is achieved by adjusting the bY length. In addition, achieving the desired performance by changing only a specific parameter saves time and cost. Similarly, it is also possible to use the same antenna for different communication protocols or systems. This feature increases the flexibility and compatibility of the design.

Normalized gain graphs obtained using the Ansys HFSS program are given in Figures 24, 25 and 26. It was observed that the designed tri-band microstrip antenna reached gain values of 5.40 dB at 1.55 GHz frequency, 4.40 dB at 2 GHz frequency and 3.78 dB at 2.92 GHz frequency.

Gain Plot of The Microstrip Antenna at 1.55GHz

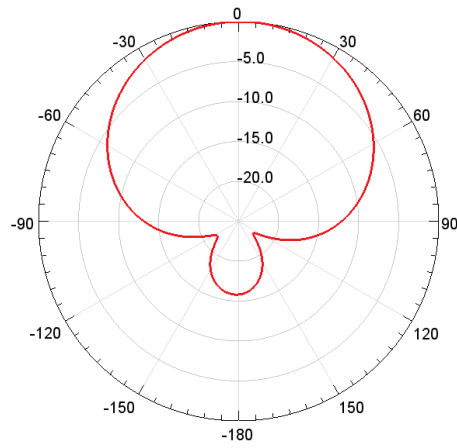


Figure 23: Gain Plot of The Tri-Band Microstrip Antenna at 1.55 GHz

Gain Plot of The Microstrip Antenna at 2.00GHz

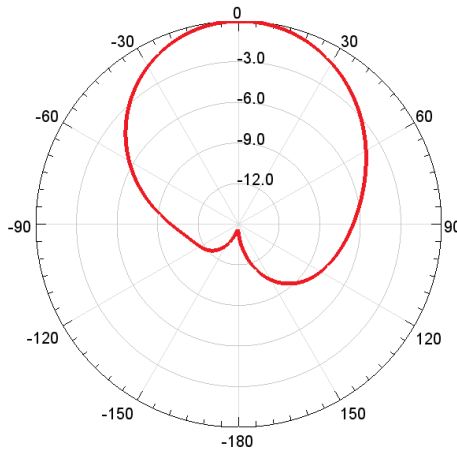


Figure 24: Gain Plot of The Tri-Band Microstrip Antenna at 2.00 GHz

Gain Plot of The Microstrip Antenna at 2.92GHz

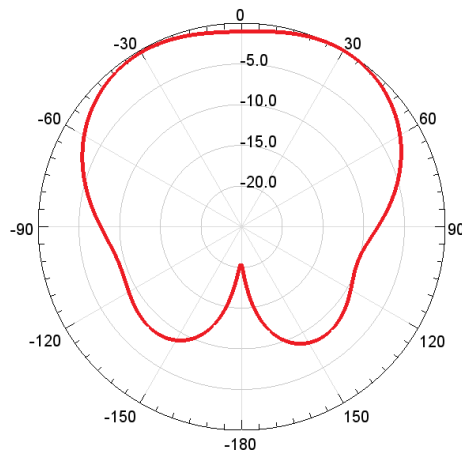


Figure 25: Gain Plot of The Tri-Band Microstrip Antenna at 2.92 GHz

4.4 IMPEDANCE MATCHING AND INSET FEEDING

Microstrip antennas, due to their high impedance values, are fed with a standard 50-ohm impedance coaxial cable. The feed point in the design is shown in the figure 26.

In microstrip antennas, impedance is usually high at points close to the patch edge of the antenna. As the feed point is moved further inward on the patch, impedance decreases. For this reason, the inset feed method is usually included in designs to reduce the input impedance to 50 ohms and optimize energy transfer [3]. This detail is also included in the designed triple-band microstrip antenna as seen in figure 26 and table 2 values. Inset feed makes the antenna impedance compatible with 50 ohms by designing the feed point of the patch antenna further inward on the patch. It is necessary to achieve maximum power transfer and minimum reflection [3].

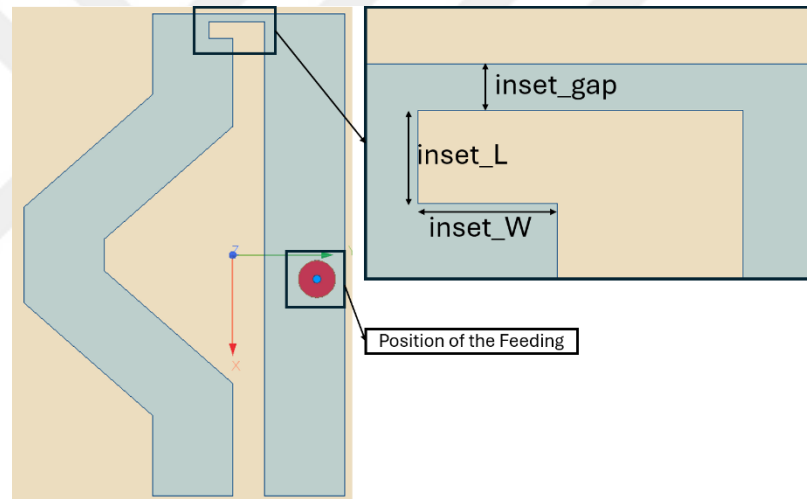


Figure 26: Inset Feeding of the Tri-Band Microstrip Antenna

Table 2: Dimension of Inset Feeding on the Tri-Band Microstrip Antenna

Description	Length (mm)
inset_W	3 mm
inset_L	2 mm
Inset_gap	1 mm

4.5 IMPLEMENTATION AND EXPERIMENTAL VALIDATION

In the implementation step of the antenna, I chose to use Rogers RT5880 dielectric substrate, which is suitable for high-frequency applications. The technical specifications of this selected substrate were discussed under heading 4.2. For the

antenna patch, I used a copper strip with high electrical conductivity. Antenna dimensions are adjusted using a digital caliper for precision. Then, I placed the patch and ground structures on the substrate in a way that would be suitable for HFSS modeling. In particular, determining the feed point location of the antenna is one of the important steps of the design. In order for the antenna to exchange energy most efficiently, I placed a coaxial feed line at the calculated optimum point of the patch. Figure 27 is the photo of the antenna implementation. After the implementation process was completed, I made measurements with VNA to test the performance of the antenna. VNA results are given in Figure 28. When the S11 results obtained from VNA are examined, it is seen that the antenna has -14.93 dB, -15.57 dB and -19.39 dB reflection coefficients at frequencies of 1.55 GHz, 2.00 GHz and 2.92 GHz, respectively. These values are close to the simulation results.

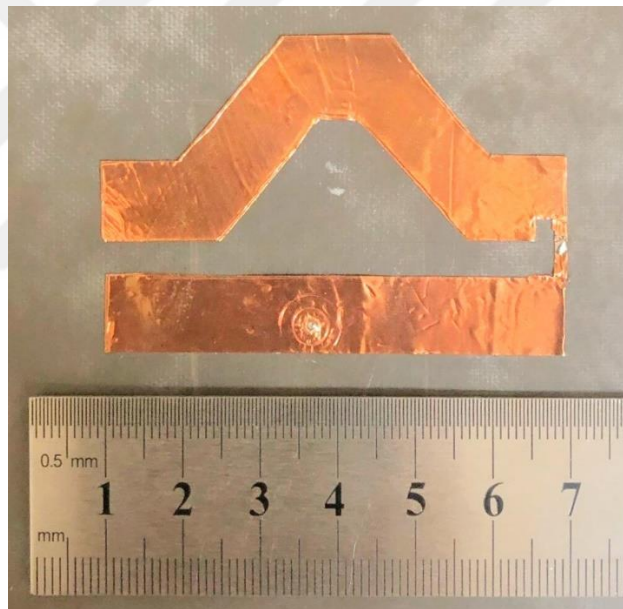


Figure 27: Photo of the Triple Band Microstrip Antenna

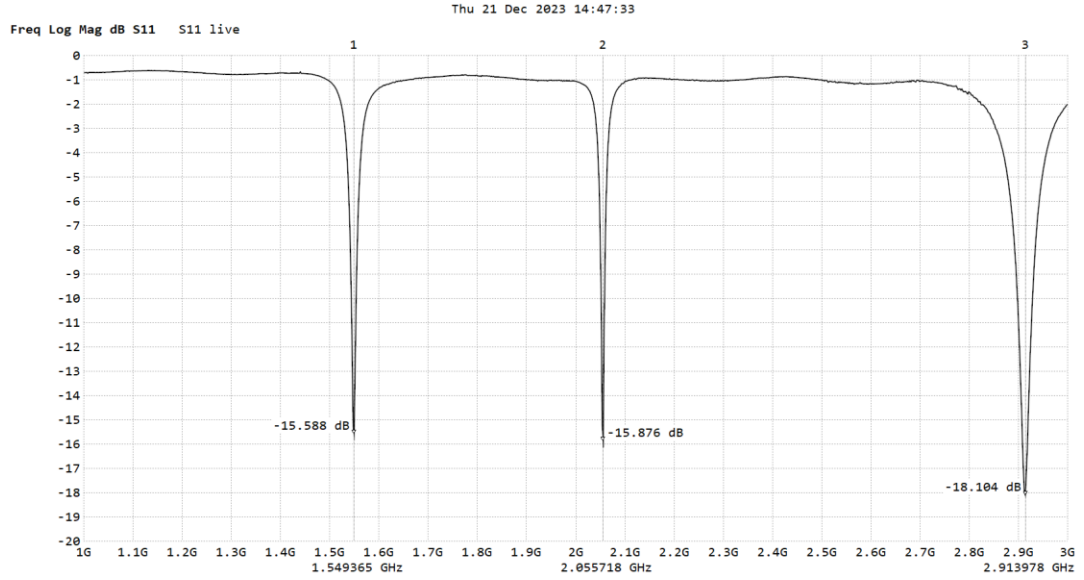


Figure 28: VNA |S11| Graph of Tri-Band Microstrip Antenna

In Figure 29, the comparison of the |S11| values obtained from HFSS with the values obtained from the measurements is made. Thus, it is observed that the values are compatible and close to each other.

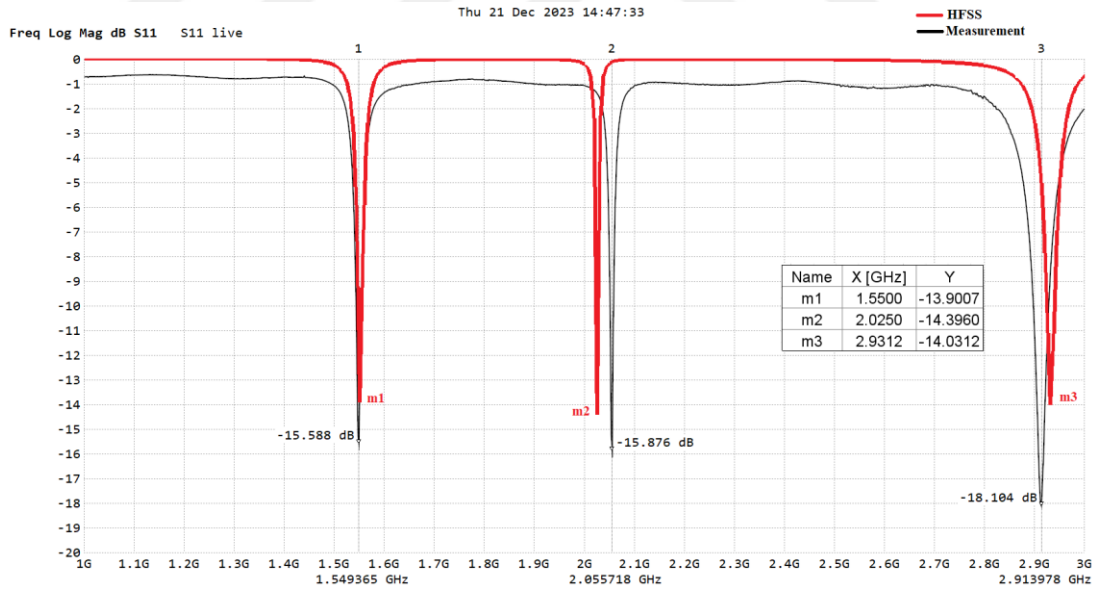


Figure 29: |S11| results of HFSS and VNA

Figures 30, 31, and 32 show the normalized total power gain measurements of the antenna at three different frequencies, along with their comparison to the simulation results. Since the measurements were not conducted in an anechoic chamber, the results, especially at higher frequencies, have been affected.

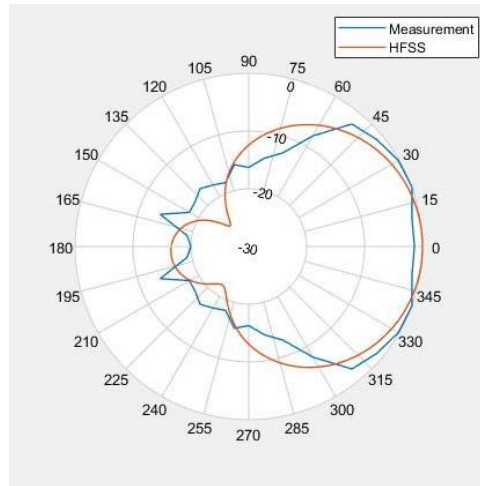


Figure 30: Total Power Density at 1.55 GHz

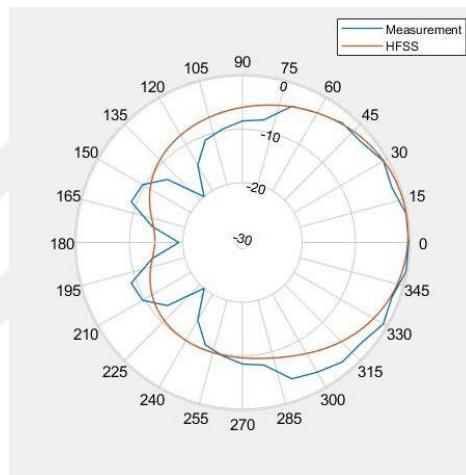


Figure 31: Total Power Density at 2.00 GHz

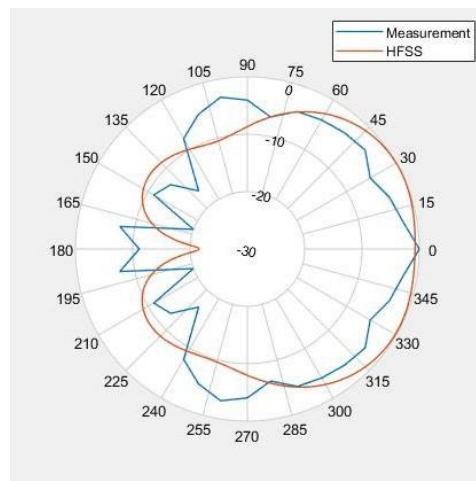


Figure 32: Total Power Density at 2.92 GHz

CHAPTER V

CONCLUSION

This thesis study is written on antennas, which are a big part of wireless communication, and after providing detailed information about antennas, it focuses on microstrip antennas. Considering the current structural developments of microstrip antennas, the general concept is examined, then the dual and triple band structures are focused on. A new triple band microstrip antenna is designed by taking into account the methods, design processes and examples of obtaining these antenna structures. First, this antenna, which was designed and analysed in the HFSS program, was observed to work effectively in the 1.55 GHz, 2.00 GHz and 2.92 GHz bands, and then its gain graphs were examined. Since the use of triple band microstrip antennas provides advantages in many areas, this microstrip antenna design can also be used successfully in these areas. When the antenna is examined parametrically, results that will create advantages in the field of use depending on two length variables are obtained. In these results, while two bands are fixed depending on only one length variable, changes in the resonance frequency of the other band are seen. In this way, it stands out among other current designs with its adjustable feature in resonance frequency. After this designed antenna was implemented, VNA measurements yielded results close to simulation measurements. The proposed tri-band microstrip antenna is suitable for 5G and Wi-MAX applications.

REFERENCES

- [1] BALANIS C. A. (2016), *Antenna Theory: Analysis and Design*, Fourth Edition, Wiley, New Jersey.
- [2] GRIFFITHS D. J. (2017), *Introduction to Electrodynamics*, Fourth Edition, Cambridge University Press, Cambridge.
- [3] POZAR D. M. (2012), *Microwave Engineering*, Third Edition, Wiley, New Jersey.
- [4] KRAUS J. D. and MARHEFKA R. J. (2002), *Antennas: For All Applications*, Third Edition, McGraw-Hill, New York.
- [5] JOHNSON R. C. (1993), *Antenna Engineering Handbook*, Third Edition, McGraw-Hill, New York.
- [6] STUTZMAN W. L. and THIELE G. A. (2012), *Antenna Theory and Design*, Third Edition, Wiley, New Jersey.
- [7] RAMO S., WHINNERY J. R., and VAN DUZER T. (1994), *Fields and Waves in Communication Electronics*, Second Edition, Wiley, New Jersey.
- [8] GONZALEZ G. (1996), *Microwave Transistor Amplifiers: Analysis and Design*, Second Edition, Prentice Hall, New Jersey.
- [9] BROWN L. (1999), *A Radar History of World War II: Technical and Military Imperatives*, Institute of Physics Publishing, Bristol.
- [10] NASA (1965), *National Aeronautics and Space Administration, Intelsat I (Early Bird) Communications Satellite*, NASA Archives, Washington D.C.
- [11] DESCHAMPS G. A. (1953), "Microstrip Microwave Antennas", *Proceedings of the Third USAF Symposium on Antennas*.
- [12] SULLIVAN P. and SCHAUBERT D. H. (1986), "Aperture-Coupled Microstrip Antennas", *IEEE Transactions on Antennas and Propagation*, Vol. AP-34, pp. 977-984.
- [13] VOLAKIS, J. L. (2007), *Antenna Engineering Handbook*, Fourth Edition, McGraw-Hill, New York.
- [14] CARR J. J. (2001), *Practical Antenna Handbook*, Fourth Edition, McGraw-Hill, New York.

- [15] KUMAR and RAY K. P. (2003), *Broadband Microstrip Antennas*, Artech House, Boston.
- [16] VERMA Ramesh Kumar and SRIVASTAVA D. K. (2020), “Triple-band microstrip antenna design”, *Journal of Wireless Personal Communications*, Vol. 112, No. 3, pp. 877-892.
- [17] WANG J. and LI Q. (2019), “Triple-band microstrip antenna for high efficiency and low input impedance”, *Journal of Antenna Research*, Vol. 24, No. 3, pp. 456-467.
- [18] SMITH J. and DOE A. and JOHNSON R. (2020), “Triple-Band Microstrip Antenna for WLAN/WiMAX Applications”, *Journal of Wireless Communication Systems*, Vol. 12, No. 3, pp. 456-467.
- [19] ELLIOTT R. S. (1981), *Antenna Theory and Design*, First Edition, Wiley, New York.
- [20] LONNGREN K. E., SAVOV S. V. and JOST R. J. (2007), *Fundamentals of Electromagnetics with Matlab*, Second Edition, SciTech Publishing, Raleigh.
- [21] JOHNSON H. W. and GRAHAM M. (1993), *High-Speed Digital Design: A Handbook of Black Magic*, Prentice Hall, Upper Saddle River.
- [22] COLLIN R. E. (2001), *Foundations for Microwave Engineering*, Second Edition, IEEE Press, New York.
- [23] HARRINGTON R. F. (2003), *Time-Harmonic Electromagnetic Fields*, First Edition, Wiley, New Jersey.
- [24] ULABY F. T., MOORE R. K. and K. A. (2010), *Microwave Remote Sensing: Active and Passive* (Vol. 1 and 2), Artech House, Boston.
- [25] COX S. M. (1991), *Antenna Arrays and Applications*, Artech House, Boston.
- [26] HANSEN R. C. (2009), *Phased Array Antennas*, Second Edition, Wiley, New Jersey.
- [27] RAO K. P. (2005), *Microstrip Antenna Design Handbook*, Artech House, Boston.
- [28] KRAUS J. D. and FLEISCH D. A. (2005), *Electromagnetics with Applications*, Fourth Edition, McGraw-Hill, New York.
- [29] HONG J. S. and LANCASTER M. J. (2001), *Microstrip Filters for RF/Microwave Applications*, Wiley, New York.
- [30] GUPTA K. C. and GARG R. (2005), *Microstrip Antenna Design Handbook*, Artech House, Boston.

- [31] JAMES J. R. and HALL P. S. (1989), *Handbook of Microstrip Antennas*, Peter Peregrinus Ltd, London.
- [32] YANG F. and LIU J. (2008), *Microstrip Antenna Design for Wireless Applications*, Wiley, Hoboken.
- [33] GUPTA K. C. and WONG K. L. (2000), *Microstrip Antenna Design for Wireless Applications*, Wiley, New York.
- [34] GARG R., BHARTIA P., ITTIPIBOON A. and BAHL I. (2001), *Microstrip Antenna Design Handbook*, Artech House, Boston.
- [35] BHADRA R. B., SHARMA A. K. and O'NEIL M. J. (2000), *Microstrip Antenna Design Handbook*, pp.100-250, Artech House, Boston.

