DESIGN OF A COMPACT MICROSTRIP ARRAY ANTENNA WITH SERIES-CORPORATE FEED BOTH-SIDED MIC NETWORK



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ABSTRACT

Research on microstrip patch antennas has increased noticeably over the last few years. Microstrip antennas present significant advantages and enhanced opportunities when compared to traditional antennas. They are lighter, occupy less space, are more cost-effective, have a lower profile, and are simpler to manufacture. Arrays enhance the overall gain, mitigate interference from specific directions, and optimize the signal-to-interference noise ratio (SINR). Arrays can be linear, circular, or planar. Planar arrays are remarkably versatile, with antenna elements arranged on a flat surface, yielding more symmetrical patterns with reduced side lobes and achieving much higher directivity.

The focus of this research is to create a compact microstrip array antenna that employs a series-corporate feed dual-sided MIC network, aimed at functioning at a frequency of 10 GHz. Consequently, the primary target of this thesis is to create, analyze, and optimize a 2×4 microstrip array antenna. To explore this objective, the feeding distance of the 2×2 array corporate MIC feed on both sides (0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ) is maintained consistently across patches, both horizontally and vertically, and networks have been developed. By incorporating four elements into a 2×2 array with series feeding, the design will be transformed into a 2×4 array with corporate-series feeding.

A 2×4 array is designed using a corporate-series feeding technique; both the advantages of corporate and series feeding are obtained from this work. The corporate-series feed provided the highest gain and moderate transmission line loss among the three (series feed, corporate feed, and series-corporate feed).

The project utilizes an inset feed line, which minimizes antenna size while enhancing gain, directivity, and the reflection coefficient. There is no requirement for impedance-matched transmission lines within the feed circuit. In this endeavor, a "both-sided" circuit technique is utilized, involving the arrangement of various categories of transmission lines on either side of the dielectric substrate, which is crucial for array antenna feed systems. Microstrip lines are positioned on the upper side of the dielectric substrate, whereas slot lines are situated on the reverse side. Through electromagnetic coupling, a novel feeding mechanism is developed.

Previously, the array was a two-sided corporation. This array antenna has a two-sided series-corporate array (upper side and lower side) connected by a slot-microstrip and a

microstrip-slot branch line. Each patch element is connected by a 2.4 mm-width microstrip line in the whole network.

This array structure is simple. It does not require structural changes through the use of stubs, transformers, multi-section transformers, taper lines, inductors, or capacitors. No impedance-matching line is necessary throughout the complete feed system.

Outstanding characteristics that significantly diminish undesirable cross-polarization have been verified. In particular, the advanced design system (ADS) developed by Agilent Technology, which is based on the method of moments, has been employed to confirm and assess the sizes of the suggested array antenna by utilizing the gain and directivity enhancement of antenna arrays.

বিমূর্ত

সাম্প্রতিক বছরগুলিতে মাইক্রোস্ট্রিপ প্যাচ অ্যান্টেনার গবেষণা উল্লেখযোগ্যভাবে বৃদ্ধি পেয়েছে। মাইক্রোস্ট্রিপ অ্যান্টেনাগুলি প্রচলিত অ্যান্টেনার তুলনায় আরও উল্লেখযোগ্য সুবিধা এবং উন্নত সম্ভাবনা সরবরাহ করে। তারা হালকা, একটি ছোট ভলিউম আছে, খরচ কম, একটি নিম্ন প্রোফাইল আছে, এবং নির্মাণ করা সহজ. অ্যারে সামগ্রিক লাভ বাড়ায়, দিকনির্দেশের একটি নির্দিষ্ট সেট থেকে হস্তক্ষেপ বাতিল করে, সংকেত থেকে হস্তক্ষেপ প্লাস নয়েজ রেশিও (SINR) সর্বাধিক করে। অ্যারেগুলি রৈখিক, বৃত্তাকার এবং প্ল্যানার। প্ল্যানার অ্যারেগুলি আরও বহুমুখী, কিছু প্ল্যানার পৃষ্ঠের উপর সাজানো অ্যান্টেনা উপাদানগুলি, নীচের দিকের লোবগুলির সাথে আরও প্রতিসম প্যাটার্ন প্রদান করে এবং অনেক উচ্চতর ডিরেক্টিভিটি প্রদান করে।

এই গবেষণা কাজের লক্ষ্য হল 10 GHz ফ্রিকোয়েন্সিতে কাজ করার জন্য সিরিজ-কর্পোরেট ফিড উভয়-পার্শ্বযুক্ত MIC নেটওয়ার্ক সহ একটি কমপ্যাক্ট মাইক্রোস্ট্রিপ অ্যারে অ্যান্টেনা ডিজাইন করা। থিসিসের মূল উদ্দেশ্য হল 2×4 অ্যারে অ্যান্টেনা ডিজাইন, বিশ্লেষণ এবং অপ্টিমাইজ করা। এই উদ্দেশ্যটি তদন্ত করার জন্য, প্যাচগুলির মধ্যে উভয় পার্শ্বযুক্ত MIC ফিড 2×2 অ্যারে কর্পোরেট ফিডিং দূরত্ব (0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ) অনুভূমিকভাবে এবং উল্লম্বভাবে একই রাখা হয়েছে, নেটওয়ার্কগুলি ডিজাইন করা হয়েছে। সিরিজ ফিডিং সহ একটি 2×2 অ্যারে সহ চারটি উপাদান অন্তর্ভুক্ত করে ডিজাইনটি একটি 2×4 অ্যারে কর্পোরেট -সিরিজ ফিডিং হবে।

2×4 অ্যারে কর্পোরেট-সিরিজ ফিডিং কৌশলের সাথে ডিজাইন করা হয়েছে, এই প্রকল্প থেকে কর্পোরেট এবং সিরিজের উভয় সুবিধাই পাওয়া যায়। কর্পোরেট-সিরিজ ফিড (সিরিজ ফিড, কর্পোরেট ফিড, এবং সিরিজ- কর্পোরেট ফিড), তিনটির মধ্যে সর্বোচ্চ লাভ এবং মাঝারি ট্রান্সমিশন লাইন লস প্রদান করেছে।

প্রকল্পটি ইনসেট ফিড লাইন ব্যবহার করে এটি অ্যান্টেনার আকার হ্রাস করে এবং লাভ, ডিরেক্টিভিটি এবং প্রতিফলন সহগকে আরও ভাল মান দেয়। ফিড সার্কিটে কোনো প্রতিবন্ধক ম্যাচিং ট্রান্সমিশন লাইনের প্রয়োজন নেই। এই প্রকল্পে, "উভ-পার্শ্বযুক্ত" সার্কিট কৌশল, যা অন্তরক সাবস্ট্রেটের উভয় পাশে বিভিন্ন ধরণের ট্রান্সমিশন লাইন স্থাপন করে অ্যারে অ্যান্টেনা ফিড সিস্টেমের জন্য ব্যবহৃত হয়। অন্তরক সাবস্ট্রেটের সামনের পৃষ্ঠে মাইক্রোস্ট্রিপ লাইন ব্যবহার করা হয়, এবং স্লট লাইনগুলি পিছনের দিকে স্থাপন করা হয়। ইলেক্ট্রোম্যাগনেটিক কাপলিংয়ের মাধ্যমে, একটি নতুন ফিড সিস্টেম তৈরি করা হয়।

এর আগে, আমরা উভয় পার্শ্বযুক্ত কর্পোরেট অ্যারে দেখেছি। এই অ্যারে অ্যান্টেনায় উভয় পার্শ্বযুক্ত সিরিজ-কর্পোরেট অ্যারে (উপরের দিক এবং নীচের দিকে) স্লট-মাইক্রোস্ট্রিপ ও মাইক্রোস্ট্রিপ-

স্লট, লাইন দ্বারা সংযুক্ত রয়েছে। প্রতিটি প্যাচ উপাদান পুরো নেটওয়ার্কে 2.4 mm প্রস্থ মাইক্রোস্ট্রিপ লাইন দ্বারা সংযুক্ত।

এই অ্যারে গঠন সহজ, এর জন্য স্টাব, ট্রান্সফরমার, মাল্টিসেকশন ট্রান্সফরমার, টেপার লাইন, ইন্ডাক্টর, ক্যাপাসিটরগুলির মাধ্যমে কাঠামোগত পরিবর্তনের প্রয়োজন নেই। সম্পূর্ণ ফিড সিস্টেমে কোনও প্রতিবন্ধক ম্যাচিং লাইনের প্রয়োজন নেই। অবাঞ্ছিত ক্রস-মেরুকরণকে উল্লেখযোগ্যভাবে হ্রাস করার চমৎকার বৈশিষ্ট্যগুলি নিশ্চিত করা হয়েছে। বিশেষ করে, অ্যাজিলেন্টের মোমেন্টস ভিত্তিক Advanced Design System (ADS) পদ্ধতিটি প্রস্তাবিত অ্যারে অ্যান্টেনার মাত্রা যাচাই এবং মূল্যায়ন করতে ব্যবহার করা হয়েছে। অ্যান্টেনা অ্যারে ব্যবহার করে লাভ এবং ডিরেক্টিভিটি বৃদ্ধি করা হয়।

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ABBREVIATIONS

SINR	Signal to Interference plus Noise Ratio
1G	1st Generation
SMS	Short Message Service
3G	3rd Generation
4G	4th Generation
LTE-A	Long Term Evolution- Advanced
5G	5th Generation
MMIC	Monolithic Microwave Integrated Circuit
DOA	Direction of Arrival
DOF	Degree of Freedom
ULA	Uniform Linear Antenna
SLL	Side Lobe Level
DGS	Defected Ground Structure
VSWR	Voltage Standing Wave Ratio
ADS	Advanced Design Software
LSA	Long Slot Antenna
SWR	Standing Wave Ratio
IEC	International Electro Technical Commission
MW	Microstrip line Width
SW	Slot line Width
LM	Length of Microstrip line extension over Slot line in Microstrip–slot branch circuit
MIC	Microwave Integrated Circuit
WLAN	Wireless Local Area Networks

Chapter 1: INTRODUCTION

1.1 Overview

Since Hertz's discovery of electromagnetic propagation in 1888, antennas have been utilized to transmit information from one place to another across space. According to the definitions established by the IEEE standard, an antenna, also referred to as an aerial, is described as "a system for emitting or capturing radio waves" [1]. In more straightforward language, an antenna serves as a bridge between an electromagnetic wave traveling through space and a guided medium. An antenna acts as a transducer that adapts the impedance of a guiding device to the impedance of space. In recent decades, there has been growing interest in the development of more complex antenna systems. Nowadays, these systems can be used as sensors, such as detectors or radars, and also in personal communication (fixed or mobile), instrumentation equipment, measurement purposes, satellite communication, and space exploration.

An antenna array consists of a systematic arrangement of identical antennas designed to produce radiation of a specific shape. With an increased number of radiating elements, the overall radiated power is enhanced. Consequently, the potential combinations are numerous, offering a diverse range of performances necessary for various applications. Antenna arrays incorporate multiple elements, including horns, wires, patches, parabolic structures, and helices. It is evident that a collection of antennas requires more space than a single antenna element, and its radiation pattern becomes narrower due to the increase in directivity associated with a larger surface area. Additionally, the antenna array yields greater gain [1].

1.2 Background

An antenna is a crucial element in a wireless communication system. It functions as a transducer, converting electromagnetic energy into electrical energy and the other way around. It also serves as a directional device in a wireless communication system, enhancing electromagnetic energy, transmitted or received, in one direction and suppressing it in another direction since various noise components are present in space that weaken the signal [2].

The discovery of electromagnetism is often attributed to Hans Christian Ørsted, who in 1819 found that a wire carrying an electric current could alter the direction of a magnetic compass needle. In the year 1840, Joseph Henry identified high-frequency electric oscillations occurring away from their origins. In 1842, Joseph Henry, the creator of wire telegraphy, invented wire antennas [3]. By lighting a spark in a wire circuit in his room, which was 30 feet high above the cellar, he discovered that a current was running in a parallel circuit. The current produced could create a magnetic effect in a needle. In 1861, James Maxwell mathematically characterized electromagnetic waves, subsequently presenting his theory at the Royal Society of London in December 1864, which was subsequently disclosed in 1873. In 1875, Edison invented a grounded, vertical, top-loaded antenna and used it in a communication system [4]. He used the technique to hear distant key clicks. By using a similar setup later, A. E. Dolbear transmitted speech and codes [5].

In 1894, the coaxial cable was invented by Nikola Tesla in the USA. Although the contributions of other renowned scientists, such as Heinrich Rudolf Hertz and Sir Oliver Lodge, Popov, Augusto Wright, Lebedev, and Pampa, cannot be ignored, Guglielmo Marconi's demonstration in 1896 is taken into account as the most important incident in the history of wireless communication. Marconi established a 1.7-mile radio telegraph system on behalf of the British Post Office. In the subsequent year, he launched the first enduring wireless station at the Isle of Wight, making it possible to communicate with maritime vessels. The following year, he introduced a second station in Bournemouth. In 2013, George Keyser described this system in his book as "the first permanent point-to-point wireless link" [6]. In 1897, Karl Ferdinand Braun unveiled the Cathode Ray Tube, which featured magnetic deflection and a CRT oscillator.

On December 12, 1901, Marconi discovered the wireless communication process. He transmitted a signal over the Atlantic Ocean using a fan monopole antenna. Later, he created a capacitance antenna of 82 kHz frequency and a pyramidal stub antenna of 70 kHz frequency, respectively, in 1904 and 1905 [7]. In the year 1909, Arnold Sommerfeld provided a theoretical solution to integral equations concerning the propagation of radio waves in free space.

During World War 1, several types of antennas were utilized in aircraft, submarines, and missile launchers. Most of those were single-element wire-type antennas. It continued until the introduction of the Yagi-Uda antenna. The Yagi-Uda antenna consists of two or more parallel resonant antenna elements arranged in an end-fire configuration. It is most frequently used in a TV antenna.

In 1914, the AM modulator circuit was invented by Edwin H. Colpitts. In 1918, Edwin H. Armstrong invented the superheterodyne receiver. In 1930, Radio Detection and Ranging (RADAR) was advanced by multiple countries. In 1935, the 3 GHz multi-cavity Magnetron was created by Hans Hollmann. In 1936, Frequency Modulation was introduced by Edwin H. Armstrong. In 1937, the Klystron Oscillator was invented by Sigurd and Russell. In 1940, Harold A. Wheeler started compact antennas [8]. Their high Q factor provides a narrow bandwidth, typically achieved with small antennas. In the next ten years, broadband antennas and frequency-independent antennas were introduced. Broadband antennas (helix) were utilized as ground-based components in space-borne communication systems for transmission and reception [9].

The "Chain Home (CH)" system was established in 1940. It represented the inaugural radar network dedicated to air defense, comprising a series of radar stations. As the conflict advanced, there arose a necessity for more advanced radar technology. The SCR-270 radar, which was accessible in Hawaii, successfully identified the Japanese forces assaulting Pearl Harbor [10]. In 1944, N-connectors like BNC, TNC, and SMA were invented by Paul Neill at Bell Labs. In 1950, Strip line and Microstrip printed circuit technology were invented. In 1961, the gallium-arsenide (GaAs) semiconductor was invented by Beard and Pittman at Texas Instruments.

Historically, wireless communication began with an analog system in 1981. In the first generation (1G), phones were limited to vocal communication only [11]. In 1989, LEVINE executed an analysis and theoretical review of the radiation and losses connected with microstrip arrays. He also delivered a meticulous description of the radiation patterns and surface wave excitation for a 4-element array, which includes the effects of the feed network. Ultimately, by increasing the quantity of elements to

16, 256, and 1024, the analysis was expanded to incorporate gains, directivity, and radiation patterns for frequencies of 10, 20, 30, and 35 GHz [12].

In 1992, in the second generation (2G), a digital system was introduced, where users can communicate via text messages, also identified as "Short Message Service" (SMS) [13]. In 2001, the third generation (3G) started by expanding digital technology through multimedia in mobile phones, laptops, and PCs [14]. Multimedia encompasses high-speed internet connectivity along with significantly enhanced video and audio streaming functionalities.

From 2011, the fourth generation (4G) has been introduced to provide high-bandwidth access, and it is recognized as Long Term Evolution-Advanced (LTE-A) [11,15]. The researchers and scientists anticipated that beyond 2020, the fifth generation (5G) would come with greater capacity and implement a new spectrum [16].

Due to their various benefits, microstrip antennas are often preferred over traditional microwave antennas in many wireless applications [17]. Due to their lightweight nature, ability to conform to flat surfaces, compactness, small dimensions, and affordability, microstrip patch antennas are extensively employed in 5G communication. These antennas are designed using the "Monolithic Microwave Integrated Circuit" (MMIC) design methodology. The impedance at the input of a microstrip antenna is influenced by its geometric shape, size, and the physical characteristics of the material used. Therefore, an inset-fed microstrip patch antenna offers a means to regulate impedance through a planar feed impedance control, resulting in a significantly reduced cost for the antenna [18].

With dynamic development in wireless communication technology, the need for compact, lightweight, cost-effective, and low-profile antennas has increased significantly. Microstrip antennas were designed to suit this purpose. Microstrip antennas are constructed by placing two metallic sheets on a dielectric substrate, with one sheet functioning as the radiating patch and the other as the ground, located on opposite sides of the patch. Patches come in various geometric shapes, including rectangles, circles, triangles, and squares [19].

Antenna arrays have been integrated into a diverse array of applications related to signal processing owing to their numerous advantages, which include enhanced total gain, diversity gain, cancellation of interference, steering of the beam, and direction-of-arrival (DOA) estimation [20]. In general, the performance level of an antenna array tends to improve as the number of components within the array increases. The improvement is attributed to the fact that a greater number of components yield additional degrees of freedom (DOFs).

The overall gain of an antenna array featuring uniform elements is determined by the multiplication of the gain of every individual component and the array factor. In the case of a uniform linear array (ULA), the array factor corresponds to the total number of elements present in the array; consequently, a higher number of components results in an increased gain.

1.3 Microwave Frequencies in Wireless Communication

Microwave frequencies range from 300 MHz (100 cm) to 300 GHz (0.1 cm), indicating a minor section of the extensive radio wave frequency spectrum, which extends from 3 kHz to 300 GHz. This range of 300 MHz to 300 GHz, referred to as microwave frequencies, is furthermore categorized by IEEE's radar-related term into bands such as S, C, X, Ku, K, and Ka. Like this, classifications are also utilized by other organizations, including NATO and the EU. Within the whole microwave frequency range, the maximum commonly used frequencies for communications are approximately in the range 2 to 38 GHz [21].

The allocation of the accessible frequency band among various consumers, including telecommunications, radio, armed, avionics, and satellite-based services, is managed by the International Telecommunication Union-Radio communication (ITU-R) sector. Additionally, ITU-R regulates other aspects such as maximal power or Effective Isotropic Radiated Power (EIRP), antenna radiation patterns, limitations on spurious and out-of-band emissions, geographical site exclusions, time cycle usage, channel spacing, and capacity [22].

1.4 Motivation

Microstrip patch array antennas are extensively utilized across various applications due to their excellent performance, compact size, low profile, and affordability. The feed networks attached to microstrip patch array antennas can be generally classified into parallel and series feed networks.

A parallel feed network is advantageous as it provides a wide bandwidth; however, it encounters challenges in achieving high gain because of losses incurred from a lengthy feed line [23, 24]. Furthermore, there is a limitation on the extent to which side lobe levels (SLLs) can be reduced, primarily due to unwanted radiation emanating from the feed line [25, 26]. Conversely, a series feed network experiences minimal loss owing to a shorter feed line [27–29]. Nevertheless, it proves challenging to achieve the desired power distribution ratio due to the narrow feed line, which results from the interconnection of multiple radiation elements.

The combined feed network, which integrates both parallel and series configurations, can be designed by addressing the shortcomings inherent in each type. This approach significantly simplifies the achievement of the desired power distribution ratio.

In radar and satellite communication, the antennas should be designed with high directivity features to fulfill the expectations of long-distance communication. For this purpose, a 4×1 patch array antenna has been proposed along with corporate feed technology. This antenna can operate at 10 GHz frequency, has advanced gain and a parabolic beam width, suitable for a radar system [30]. However, its applications are somewhat limited. High gain and reduced size are two essential requirements for modern wireless and satellite communication systems. A proposed 4×2 microstrip patch antenna has been made using the corporate feed technique to run at a frequency of 10 GHz. Hence, this antenna provides high gain and high return loss. A significant reduction in mutual coupling has been tested using Defective Ground Structure (DGS) [31].

The proposed and designed microstrip array antennas were a 4×1 array with a series feed, a 4×1 array with a corporate feed, and a 4×2 array with a corporate-series feed. These antennas were created to function at a 10 GHz frequency. The optimum

feeding system was decided to be a corporate-series feed, based on the simulated antenna parameters. The corporate-series feed delivered the highest gain and medium transmission line loss among the three feeds [32].

A rectangular patch array antenna has been developed utilizing a corporate-series feed technique to function at a frequency of 28 GHz, making it appropriate for 5G mobile wireless applications. The suggested antenna array comprises 16 elements activated by a single port, via a Y-Junction power divider. This design provides high bandwidth, high gain, and high radiation efficiency [33]. A proposed 8×1 array, in which each element is rectangular in shape, has been designed using the corporate feed technique to operate at 10 GHz frequency. As substrate materials, FR-4 and Rogers-3006 have been used. The results obtained from antennas using Rogers-3006 were much better compared to those using FR-4. This antenna has been targeted for applications such as an intrusion detection sensor [34].

A proposed 4-element 2×2 microstrip patch array antenna has been designed with a corporate feed technique using an inset feed line [35]. But its directivity is not very high. An antenna of the 1×2 array type and a 2×2 array antenna are designed and are fed using the N-ways Wilkinson combiner technique. A rise in the number of patches on the antenna will result in improved bandwidth and gain [36]. However, this feeding method was not straightforward. At first, a single rectangular microstrip patch antenna was created to function at a frequency of 10 GHz. Subsequently, a rectangular 1×4 array patch antenna was developed, utilizing a corporate feed, to operate at the same frequency. The spacing between the elements is $0.75\lambda_0$, which was not appropriate. It was observed that the gain increased and the beam width decreased due to the increase in elements [37]. The gain achieved by four patch elements was higher compared to that achieved by a single element. To ensure better performance, the corporate feed technique has been used [38]. The antenna's high efficiency can be guaranteed through appropriate impedance matching in both the corporate and series feed array configurations. The current density, return loss, and VSWR of a single feed patch antenna surpass those of a double feed patch antenna. These characteristics of the antenna are relevant for X-Band communication and WiMAX applications [39].

A 2×1 array antenna with series feed has been proposed, which can function at a range of frequencies of 8.1 GHz – 8.35 GHz. Initially, the antenna was designed based on specifications, but it didn't work with satellite applications. As a solution, slots were placed in the design, namely, an I slot, an inverted U slot, and a Plus slot. The results obtained were the best in the case of the Plus slot antenna, which resonates at 8.32 GHz frequency and is suitable for satellite applications [40].

A proposed 1×4 rectangular patch antenna array was designed using the corporate feed technique to radiate in X-band at 10 GHz frequency. This array antenna delivers better performance, ensuring 36% improvement in gain and better directivity, relative to a single-element antenna [41].

1.5 Objectives

The objective of this work is to create a high-gain planar 2×4 antenna with a two-sided Monolithic Integrated Circuit (MIC) to work at 10 GHz frequency using a Teflon glass fiber substrate. Specifically, the Method of Moments-based advanced design system (ADS) of Agilent Technology has been utilized to assess and verify the sizes of the suggested array antenna.

Designing a 2×4 array may provide high gain and high directivity and may reduce side lobes. The specific aims of this research work are as follows:

- To reduce antenna size and obtain better values of gain, directivity, and reflection coefficient, an inset feed line will be used.
- To prevent the mutual influence among the components, the spacing among elements in the array is done so that they are not very close to each other.

Outcomes of the Thesis Work

- The array can reduce size and obtain better values of gain, directivity, and reflection coefficient.
- Able to do impedance matching easily.
- Able to suppress the mutual coupling.

1.6 Outline of Methodology

The following flowchart outlines the step-by-step procedure for the research work. For this purpose, simulation software named Path Wave Advanced Design System (ADS) has been used.

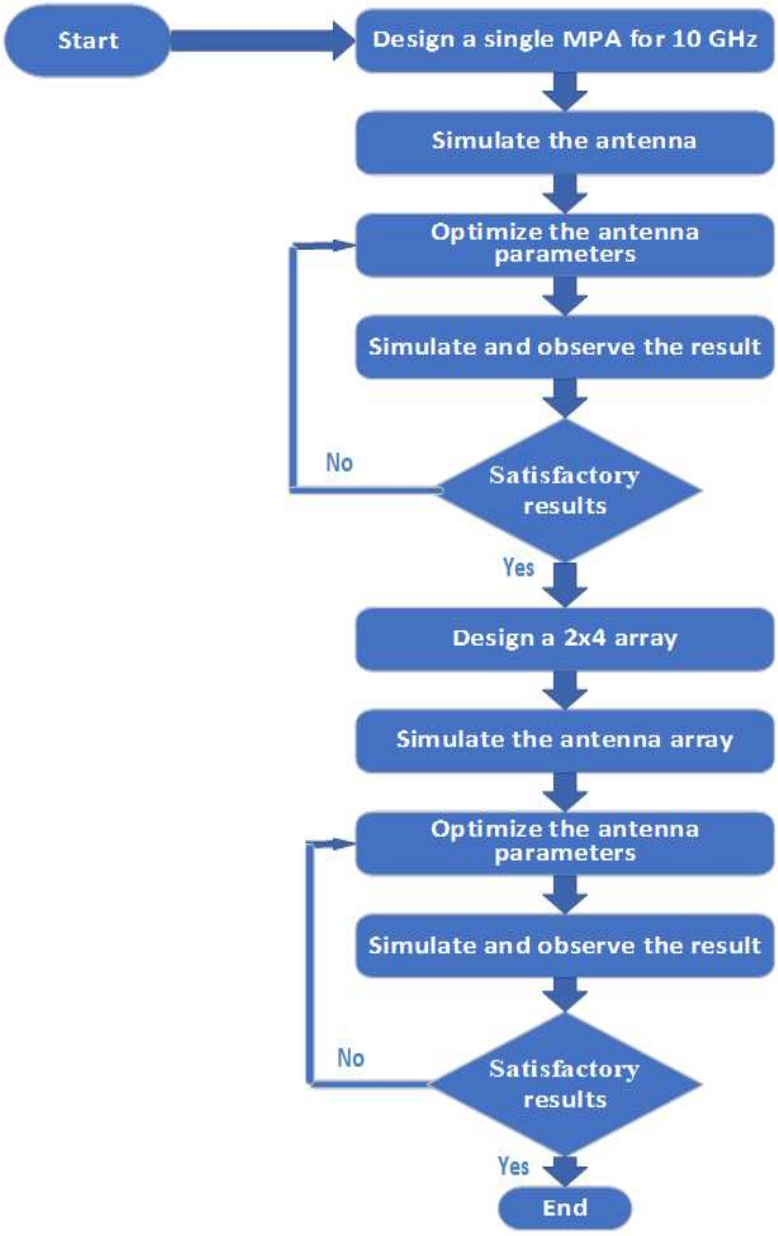


Fig. 1.0: Flow chart of a 2×4 microstrip patch array antenna.

Yes
Yes

1.7 Thesis Outline

Chapter 1: Provides an overview of the history of antennas, explains the motivation, applications, and goals, and includes a literature review on array patch antennas.

Chapter 2: The chapter includes illustrations of various microstrip patch array antennas, feeding technologies, and key parameters that will help in understanding the thesis work.

Chapter 3: The chapter describes the design of a 2×2 array microstrip patch antenna corporate feed with various inter-element distances. Data analysis regarding directivity, gain, and echo values is shown. A performance comparison of the values obtained from simulated results is presented.

Chapter 4: This chapter describes the design of a series-corporate-fed 2×4 array microstrip patch antenna with different inter-element distances. Data analysis on directivity, gain, and echo values is shown. Performance comparison of the obtained quality from simulated results is presented.

Chapter 5: This chapter presents an overall discussion of the results of the thesis work. Discussion of the limitations of this work. Furthermore, the scope of future work related to this proposed antenna is also discussed here.

Chapter 2: ANTENNA TERMINOLOGIES

To establish the context for the research presented in this dissertation and to set the stage for the contributions that will be elaborated upon in subsequent chapters, this chapter offers a concise review of the topic of array antennas. Furthermore, it provides a brief overview of essential characteristics of antennas, including polarization, radiation patterns, and feed networks**.**

2.1 Basics of Antenna

2.1.1 Input Impedance

The relationship of voltage to current at the input terminals of an antenna provides its input impedance. In transmitting mode, the power supplied by the antenna source is dissipated across the source's internal resistance, loss resistance, and the antenna's radiation resistance. The objective is to maximize the power dissipated in the radiation resistance, which effectively quantifies the power emitted by the antenna. In the receiving mode, some of the whole power captured by the antenna is either scattered or reradiated, while the rest is directed to the load.

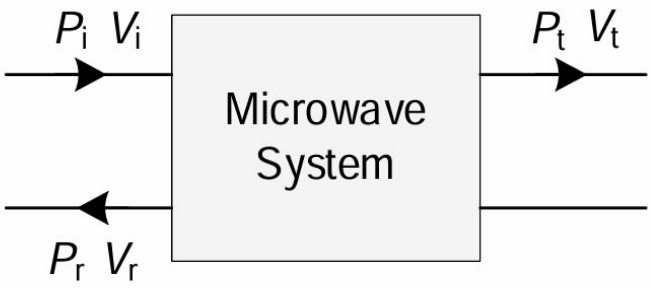


Fig. 2.1: Microwave system of an antenna.

When conjugate matching is achieved, and the antenna is aligned with the transmission line, half of the total power is directed to the antenna or received by it during transmitting and receiving modes, respectively, while the internal resistance dissipates the other half in transmitting mode or scatters it in the receiving mode. This also presumes that the line is lossless. The antenna's input-related impedance is significantly steered by frequency and functions effectively within the designated bandwidth. Additional factors such as the geometry of the antenna, its excitation

pattern, and nearby objects also significantly contribute to the determination of its input impedance.

2.1.2 Reflection Coefficient

The reflection coefficient expresses the relationship between the input signal and the reflected signal. It quantifies the extent of power that is reflected back from the antenna. A microwave process is illustrated in Fig. 2.1, where V_i denotes the incident voltage of the electromagnetic wave and V_r signifies the reflected voltage of that wave. Therefore, the voltage reflection coefficient Γ_V is described as the relationship of the reflected voltage to the incident voltage, as expressed in the following equation:

$$\Gamma_v = \frac{V_r}{V_i} \tag{2.1}$$

It can also be observed from Fig. 2.1 that Pi is indicative of the incident power level of the electromagnetic wave, while P_r denotes the reflected power of the wave. Thus, the power reflection coefficient Γ_p is described as the relationship of the reflected power to the incident power, as expressed in the following equation:

$$\Gamma_p = \frac{P_r}{P_i} \tag{2.2}$$

The reflection coefficient is typically represented in decibels (dB), with a value of -10 dB being deemed acceptable, indicating that only 10% of the total power is reflected. The voltage reflection coefficient is associated with the power reflection coefficient, which the subsequent equation can describe:

$$20 \log\Gamma_v = 10 \log\Gamma_p \tag{2.3}$$

2.1.3 Transmission Coefficient

The proportion of the signal that is sent relative to the input signal is known as the transmission coefficient. As indicated by its name, it quantifies the extent to which the feed power is effectively transmitted to the antenna. Ideally, this value should be maximized, and when represented in decibels (dB), the optimal value is 0 dB, meaning that all power is transmitted without any reflection. The T parameter is utilized to characterize this transmission coefficient; it quantifies the quantity of power

transmitted from the input port to the output port. The following equation represents the transmission coefficient of the microwave system depicted in Fig. 2.1:

$$T_v = \frac{V_t}{V_i} \tag{2.4}$$

$$T_p = \frac{P_t}{P_i} \tag{2.5}$$

Here, P_t is the transmitted power of the electromagnetic wave, and V_t is the transmitted voltage of the wave. T_V is the transmission coefficient for voltage transmission, and T_p is the transmission coefficient for power transmission.

2.1.4 VSWR

As |Γ| rises, the ratio of V_{max} to V_{min} also rises; thus, the assessment of the line's mismatch is mentioned as the standing wave ratio (SWR), which can be described as:

$$\text{SWR} = \frac{V_{max}}{V_{min}} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{2.6}$$

This measurement is commonly referred to as the voltage standing wave ratio (VSWR).

SWR is a real number such that $1 \leq \text{SWR} \leq \propto$

SWR = 1 implies a matched load.

2.1.5 Return Loss

Return loss (R_L) is a number that denotes how much of the input power is reflected. Since the word loss is in the name, the formula is designed so that it becomes a positive number. The formula is as follows:

$$R_L = 10 \log_{10} \frac{P_r}{P_i} = 20 \log_{10} \frac{Vr}{Vi} \tag{2.7}$$

In this context, R_L represents the return loss measured in dB, P_i denotes the incident power of the electromagnetic wave, and P_r signifies the reflected power of the wave. Additionally, V_i refers to the incident voltage of the electromagnetic wave, while V_r indicates the reflected voltage of the wave. It is important to note that the reflection coefficient, VSWR, and return loss all reflect the extent of power that is reflected from the antenna terminal. Their values may differ based on the specific formula used.

Typically, return loss is revealed in 10 dB. A single-port antenna has its return loss denoted in dB as S_{11}, which represents the relation of the output voltage at port-1 to the voltage entering port-1. This is also recognized as a measure of the power reflected from port-1.

2.1.6 Radiation Pattern

The term "antenna pattern" is another name for radiation pattern. It describes the antenna's efficiency in transmitting or receiving signals in a particular direction. This direction is represented as an operation of spatial coordinates, specifically the azimuth angle (horizontal diagram) and the elevation angle or zenith angle (vertical diagram), as shown in Fig. 2.2. The azimuth angle and elevation angle are represented by φ and θ [41]. In Fig. 2.2, the antenna is situated at the source of the three-dimensional spherical coordinate system. Components of the radiation pattern are known as lobes. These lobes are categorized into major (main), minor, side, and back lobes, as illustrated in Fig. 2.3 [42].

The path of highest radiation is referred to as the major lobe, which is also acquainted as the main lobe. The other lobes are identified as minor lobes. The side lobes and back lobes are considered unwanted radiation. The intensity of radiation from these lobes is less than that of the main lobe. The back lobe is found behind the beam of the antenna [41].

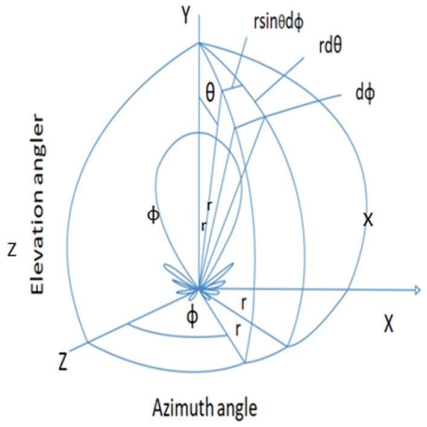


Fig. 2.2: Three-dimensional coordinate system.

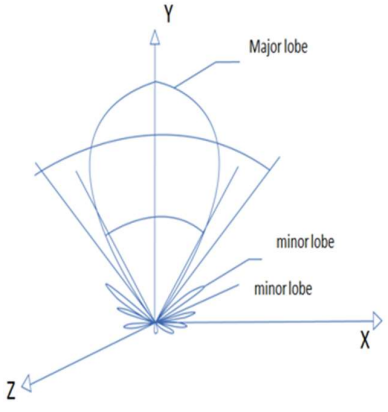


Fig. 2.3: Radiation lobes.

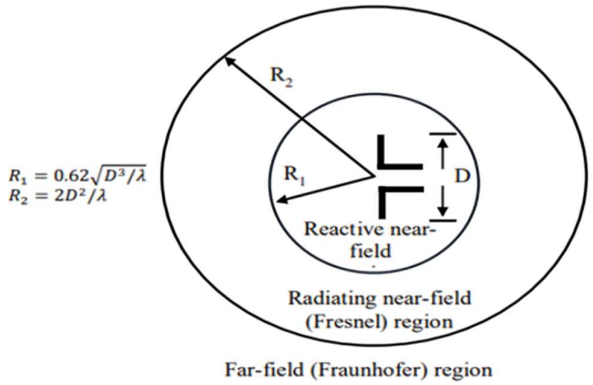


Fig. 2.4: Field region of antenna.

2.1.7 Antenna Regions

The shape of the electromagnetic field, referred to as the field pattern, is directly associated with the size of the antenna and the detachment from the respective antenna. Two categories of energy (radiant energy and reactive energy) are connected to the encircling electromagnetic field, which is categorized into three zones defined by their boundary as depicted in Fig. 2.4 [43]:

i. Reactive Near-Field

ii. Radiating Near-Field (Fresnel Region)

iii. Far-Field (Fraunhofer Region)

Reactive energy prevails in the reactive near-field area, where the electric and magnetic fields are phase-shifted by 90°. No energy is lost as it is retained. The equation below illustrates the boundary of this area [43].

$$R_1 < 0.62\sqrt{\frac{D^3}{\lambda}} \tag{2.8}$$

where R_1 represents the interval from the antenna, D denotes the greatest size of the antenna, and λ signifies the wavelength. Equation 2.9 delineates the boundary of the Fresnel region, where the radiation pattern cannot be completely characterized, even though the radiating near-field prevails [43].

$$0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda} \tag{2.9}$$

where R represents the interval from the antenna, D denotes the greatest size of the antenna, and λ signifies the wavelength.

The far-field region significantly influences the characteristics and performance of antennas. In this area, the antenna radiation pattern is formed, with the electric and magnetic fields oriented perpendicularly to one another and also perpendicular to the path along which waves travel, ensuring that the wave-front of the plane wave remains consistent. Consequently, the angular field delivery does not rely on the spacing from the antenna [43]. The boundary of the far-field zone is determinate as follows [43]. The distribution of the angular field remains unaffected by the distance from the antenna.

$$R_2 \geq 2\,\frac{2D^2}{\lambda} \tag{2.10}$$

where, R_2 represents the interval from the antenna, D denotes the greatest size of the antenna, and λ signifies the wavelength.

2.1.8 Directivity and Gain

The directivity of an antenna, as stated by the International Electrotechnical Commission (IEC), is characterized as "the relationship between the average radiation intensity produced by the antenna in a specific direction and that produced in every direction." The average radiated intensity is calculated by dividing the overall power radiated by the antenna by 4π. If a direction is not provided, it is taken for granted that the direction of the peak radiated intensity is evaluated. Mathematically,

$$\text{Directivity} = \frac{U}{Uo} = \frac{4\pi U}{P} \tag{2.11}$$

$$\text{It can also be expressed as, Directivity} = \frac{P}{P_{\text{avg}}} \tag{2.12}$$

where P represents the power density at its peak value and P_{avg} denotes the average power density. Given that directivity is exclusively determined by the configuration of the antenna's radiative pattern and does not consider the potential losses that may arise in a practical antenna system, a concept known as Gain is introduced.

$$\text{Gain} = \text{efficiency} \times \text{directivity} = \text{efficiency} \times \frac{P}{P_{\text{avg}}} \tag{2.13}$$

Efficiency is characterized as the proportion of the power transmitted by the antenna compared to the power that is fed into it. Thus, for most antennas with very high efficiency, the gain is approximately equal to the guideline [44]. In general, the sharper the lobe, the higher the antenna gain.

2.1.9 Polarization

Polarization is an essential attribute of an antenna. A mismatch in polarity can lead to considerable power loss. Typically, both the far-end and near-end antennas should possess identical dimensions and types of polarization.

The electric field is pivotal in describing the polarization of any electromagnetic (EM) field. The polarization of an emitted wave is characterized as "the characteristic of an electromagnetic wave that describes the time-dependent.

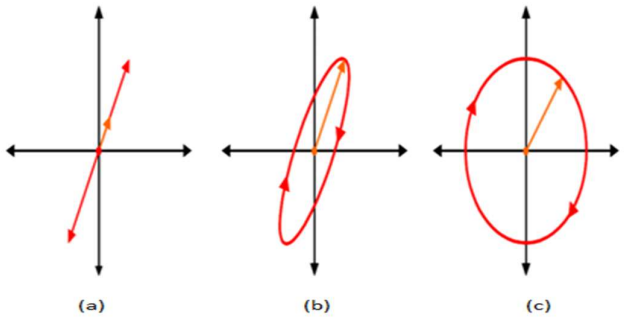


Fig. 2.5: (a) Linear polarization, (b) Elliptical polarization, (c) Circular polarization.

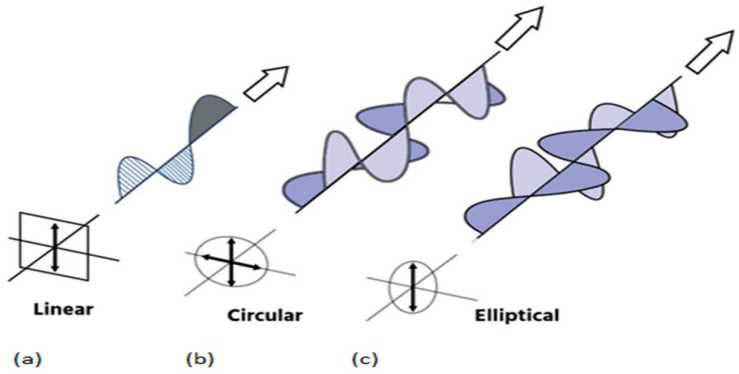


Fig. 2.6: (a) Linear Polarization, (b) Circular Polarization, (c) Elliptical Polarization.

direction and relative strength of the electric field vector; specifically, it refers to the path traced over time by the tip of the vector at a constant point in space, along with

the direction in which it is traced, as seen in the direction of propagation [44]." The polarizations frequently utilized in antennas include linear polarization (both vertical and horizontal) and elliptical polarization.

In linear polarization, the electric field (E-field) consistently points in the same direction, with the exception of a sign change, while its embodiment, the magnetic field (H-field), is oriented 90 degrees away from the E-field. When the E-field or vector is aligned parallel to the ground's surface, it is referred to as a horizontally polarized wave or antenna. Conversely, if the E-vector is oriented orthogonal to the ground's surface, it is termed a vertically polarized wave or vertically polarized antenna. The time phase difference among the two elements of a linearly polarized wave must be $n\pi$, where $n = 1, 2, 3\ldots$

Elliptical polarization can only occur when the time difference among the two elements is an odd multiple of $\pi/2$. In this scenario, if the magnitudes of the two elements (such as E and H) are identical, it represents a special case of elliptical polarization elements known as circular polarization. Otherwise, it is classified simply as elliptical polarization. Circular polarization is frequently utilized in space communications. When the vertical and horizontal components are alternately supplied in the same plane, the resulting polarization is elliptical polarization.

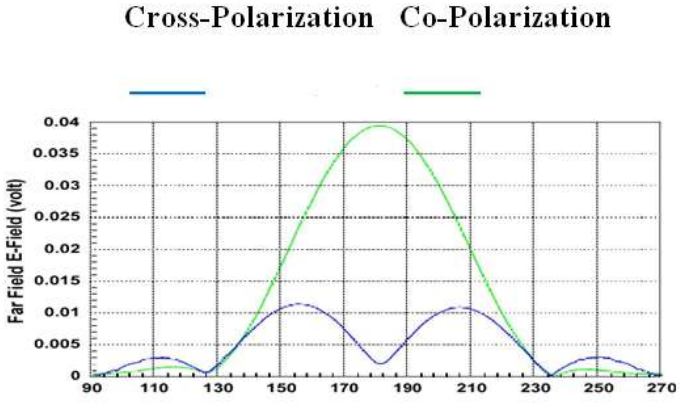


Fig. 2.7: Co-Polarization and Cross-Polarization.

2.1.10 Co-Polarization and Cross-Polarization

Co-polarization of an antenna is the polarization that the antenna creates for radiating or receiving, while cross-polarization refers to polarization perpendicular to the desired polarization.

For example, suppose an antenna is designed to emit radiation along the positive z-axis while the electric field vector fluctuates along the x-axis over time. In that case, its co-polarization is considered horizontal. Hence, the cross-polarization will be along the y-axis or in the vertical direction. The surface current delivery along with the radiation pattern is displayed in Fig. 2.7.

In the case of CP, the co-polarization and cross-polarization are defined in terms of the sense of polarization. If the intended CP is left-hand circularly polarized, then its co-polar pattern is left-hand circular polarization, and right-hand circular polarization is considered the cross-polarization pattern.

In a perfectly polarized antenna, the cross-polarization should ideally measure zero. However, purely polarized antennas do not exist in reality. The difference in decibels between the peak radiation intensity of Co-Polarization and Cross-polarization is referred to as cross-polarization. An antenna's cross polarization is defined as its power level. Usually, the value is shown as negative dB. In actual use, it provides the number of decibels by which the cross-polarization power level falls short of the intended polarization.

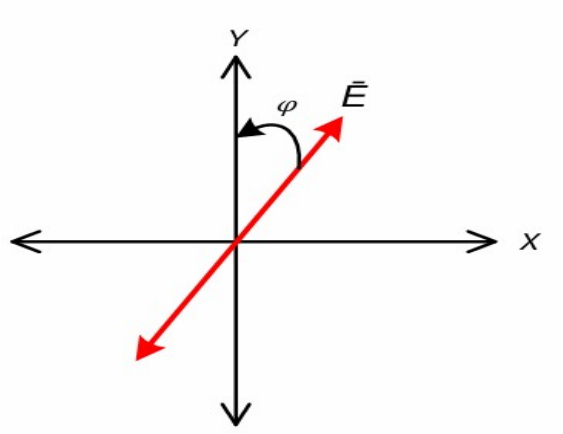


Fig. 2.8: Polarization loss factor of angle φ with y-axis.

Discrepancies in polarization result in a reduction in antenna systems known as the polarization loss factor (PLF). If ψp denotes the angle existing between two unit vectors that represent the electric field of the transmitter and the receiver antenna, then,

$$PLF = mag (\cos \psi p)^2 \quad (2.14)$$

2.1.12 Axial Ratio

The axial ratio of an antenna refers to the proportion between the major and minor axes of a circularly polarized antenna pattern. In the case of an antenna exhibiting perfect circular polarization, this ratio would equal 1 (0 dB). Conversely, if the antenna demonstrates elliptical polarization, the ratio would exceed 1 (> 0 dB). For pure linear polarization, the axial ratio is considered infinite, as the orthogonal components of the field are nonexistent.

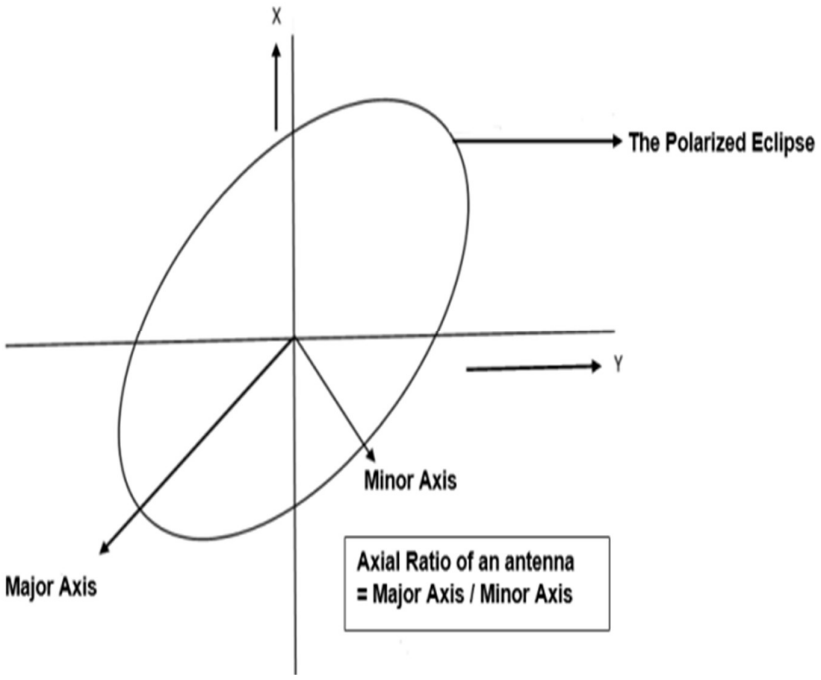


Fig. 2.9: Axial ratio of an antenna.

2.1.13 Antenna Bandwidth (BW)

The frequency spectrum range within which an antenna can demonstrate a defined level of representation is referred to as the antenna's bandwidth. This is measured in frequency units (kHz, MHz, etc.) or as a percentage of the antenna's design frequency. Numerically,

BW = maximum frequency - minimum frequency (2.15)

The maximum and minimum frequencies define the range in which the antenna can perform according to specified criteria. A typical example of such a specification is the 2:1 SWR bandwidth, which indicates that within the defined minimum and maximum frequencies, a specific antenna maintains a standing wave ratio of 2:1 or lower.

The percentage bandwidth of any antenna diminishes when the operating frequency is lowered. Consequently, for antennas functioning at reduced frequencies, the challenge lies in optimizing these antennas to accommodate a broader bandwidth.

2.1.14 Beam Width

The beam width refers to the angle formed between two points of maximum pattern located on opposite sides. Antennas offer a variety of beam widths. The most significant among these is the half-power beam width, commonly mentioned to as HPBW. HPBW is defined as the angle at which the maximum radiated pattern reaches half of its power intensity. Another notable beam width is the first null beam width,

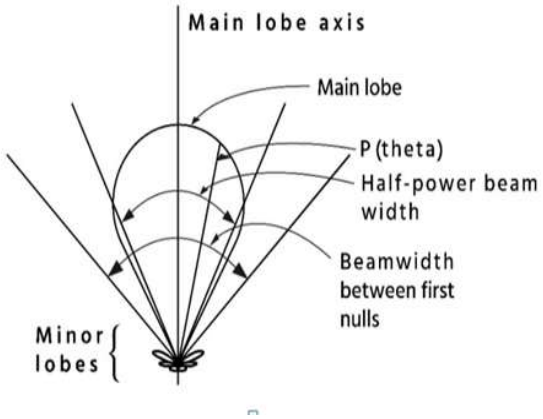


Fig. 2.10: FNBW, HPBW.

abbreviated as FNBW. FNBW represents the angle between the two points that correspond to the first nulls of the main lobe [43] pattern. The beam width is illustrated in Fig. 2.10.

2.2 Microstrip Antenna

In their fundamental structure, microstrip antennas resemble parallel plate capacitors. Both types consist of two parallel metal plates with a dielectric substrate positioned between them. In the structure of a microstrip antenna, one metal plate is infinitely elongated relative to the other, resulting in the formation of the ground plane; the lesser plate is known as the radiating patch.

The patch's dimensions are typically aligned with the frequency of the signal being conveyed, thus identifying this category of antenna as resonant antennas. This attribute gives rise to a major drawback of microstrip antennas, namely their restricted bandwidth, usually amounting to just a few percent [46] of the resonance frequency. To date, various forms of microstrip patches, including circular, rectangular, semicircular, annular, and sectoral have been effectively utilized as radiating antenna components in numerous control and communication apparatuses [46].

Fig. 2.11 illustrates the plainest form of a microstrip patch antenna, which is composed of rectangular radiating components. When the patch is energized by a feed line, charge is allocated on the lower side of the patch as well as on the ground plane.

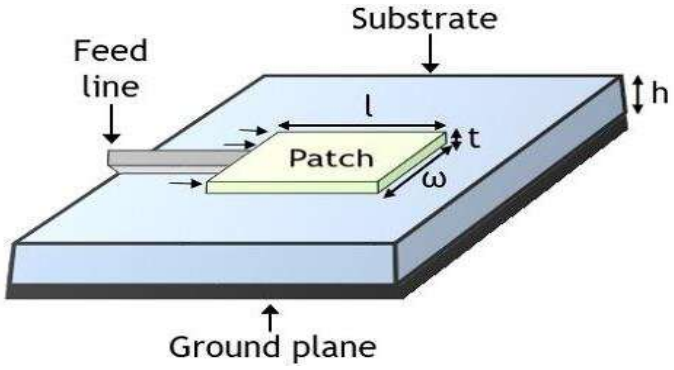


Fig. 2.11: Microstrip rectangular patch antenna.

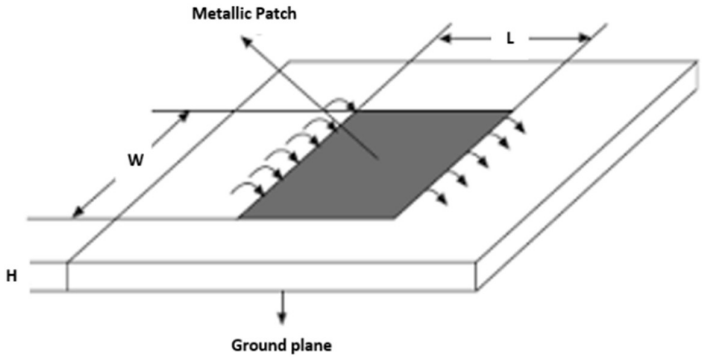


Fig. 2.12: Radiation mechanism attached to the microstrip patch.

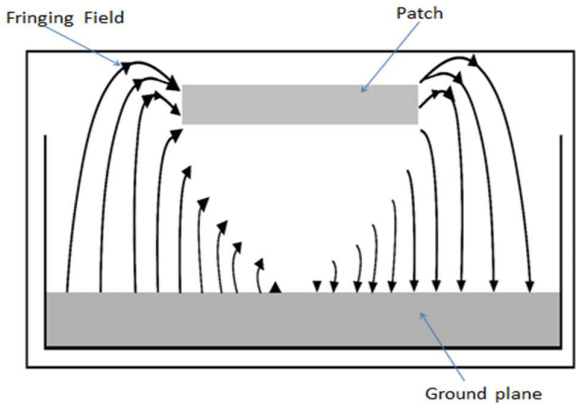


Fig. 2.13: Electric field distribution (side view) [42].

At a specific moment, the striking forces acting between the bottom of the patch and the ground plane are responsible for retaining a significant quantity of charge. Additionally, the repellent forces drive the charges towards the edges of the patch, resulting in a high charge density at those edges. These factors contribute to the formation of the fringing field. Radiation from the microstrip antenna can emanate from the fringing fields located among the edges of the patch and the ground plane [46].

Supposing that the electric field remains uniform across the breadth (W) and the depth (t) of the microstrip design, it is the patch that generates the electric field. Fig. 2.12 and 2.13 illustrate the radiation mechanism relevant to the microstrip patch and the electric field distribution (side view).

2.3 Planar Antennas

Planar antennas are fabricated on a dielectric circuit board, usually featuring ground metallization on one side. These antennas are commonly acquainted, as integrated antennas, as they are generally compatible with standard planar transmission lines, including microstrip lines, coplanar waveguides, and coplanar strip lines, and can be combined with various other circuit types. These antennas are characterized by their low profile and affordability [47].

2.4 Array Antenna

An antenna array generally offers more capabilities than a single component within the array. Arrays can be utilized to create a desired pattern that a single component might not achieve. They are recognized for their characteristics such as beam scanning, enhanced directivity, and increased gain. The arrangement of individual components in an array provides greater degrees of freedom concerning their positioning. Therefore, the geometrical configuration is the primary consideration when discussing an array. A linear array consists of all components aligned in a single row. When the components are organized in a two-dimensional plane instead of a one-dimensional line, the geometric arrangement is known as a planar array. Circular and rectangular orientations serve as prime instances of planar arrays. Non-planar arrays, such as spherical and cylindrical configurations, are also employed in specific usage, such as universe communication.

The second crucial aspect of an array antenna, following geometric orientation, is the related positioning of the separate components. The spacing among these components significantly influences the performance of the array, as the components collaborate to emit energy and establish mutual connections with each other. Typically, the distance among components is maintained as a constant; however, variations in distance have also been explored and documented. For instance, in [48], the distance between separate antennas was varied to investigate enhancements in the reduction of side lobes.

The third aspect to consider when creating an array antenna is the excitation of separate elements regarding amplitude and phase. Variations in amplitude and/or phase during the excitation of array elements are quite useful for shaping and directing

the beam. Scanning radars that are designed to detect aerial vehicles utilize this method to monitor the area, recognize, and compile fundamental data, including the distance and form of an aerial vehicle. When every element in an array is uniform, two nearly autonomous variables govern the radiation pattern of the array antenna. The initial aspect is referred to as the radiation pattern of an individual element (also known as the element pattern), while the second aspect is referred to as the array factor. The array factor represents the radiation pattern exhibited by the array if the components were substituted with isotropic radiators. The overall radiation pattern E (total) is expressed by the following equation [49].

E (total) = E (single component) × Array Factor (2.16)

2.4.1 Linear Array Factor

For any array where all components are the same, if we denote 'd' as the distance among the components and 'β' indicating the advancing phase difference among them, the linear array factor is formulated as follows:

$$\text{Linear Array Factor} = \sum_{n=1}^{N} e^{+j(n-1)(kd\cos\theta+\beta)} \quad (2.17)$$

Where "θ" represents the angle formed among the axis of the linear arrangement of antennas and the observation point in space where the radiation characteristics are assessed. Likewise, "n" denotes the total number of elements within the array. The expression $kd\cos\theta+\beta$ is collectively referred to as relative phase (φ). Relative phase is utilized to ascertain the advancing phase difference (β) among components, enabling the beam to be directed at the desired angles in space. Fig. 2.14 shows a linear array antenna.

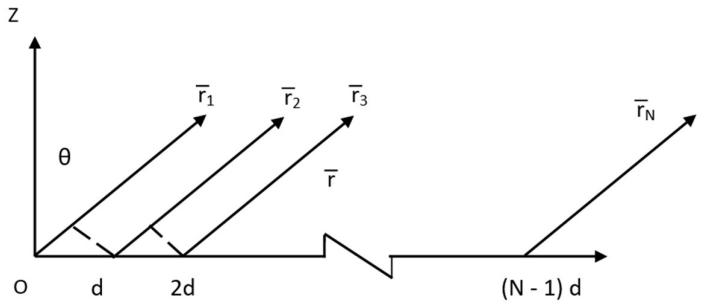


Fig. 2.14: N-element linear array.

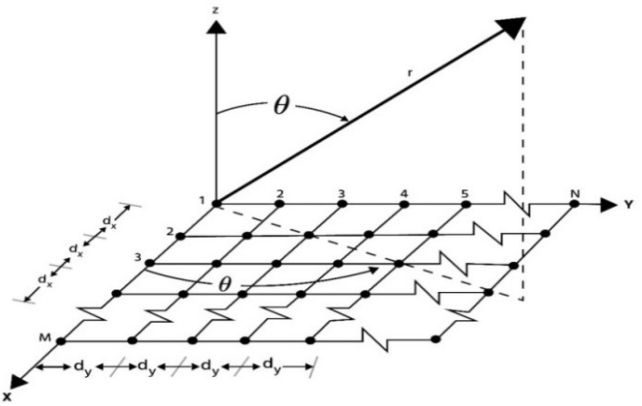


Fig. 2.15: Figure of a planar array antenna.

2.4.2 Planar Array Factor

As previously stated, when the components of the array antenna are arranged in a plane instead of being oriented in a specific direction, this type of antenna system is mentioned as a planar array antenna. Figure 2.15 illustrates a diagram of a rectangular planar array.

If "dx" and "dy" denote the distances that separate components spatially in the X and Y directions, as illustrated in fig. 2.15, then the array factor for this system [49] of components is mathematically expressed by the equation provided below.

$$AF\,(\theta, \emptyset) = A \times B \tag{2.18}$$

$$\text{where, A} = \frac{1}{M}\frac{\sin(M\varphi x)}{\sin(\varphi x)} \tag{2.19}$$

$$\text{and } B = \frac{1}{N}\frac{\sin(N\varphi x)}{\sin(\varphi x)} \tag{2.20}$$

Here, “M” and “N” signify the number of columns and rows in the array as shown in Fig. 2.15.

Similarly,

$$\varphi x = \text{kdxsin}\theta\text{cos}\emptyset + \beta x \tag{2.21}$$

$$\varphi y = \text{kdysin}\theta\text{sin}\emptyset + \beta y \tag{2.22}$$

Where “k” is the wave number which is equal to $\frac{2\pi}{\lambda}$.

The equation described above is then applied to calculate the suitable phase difference between neighboring components for the azimuthal angle "∅" and the elevation angle "θ". This will help in identifying the radiation features at any position in space encircling this rectangular planar array antenna.

2.5 Feeding Technique

According to the method of feeding, arrays can be classified in the following ways:

a) Series feed network

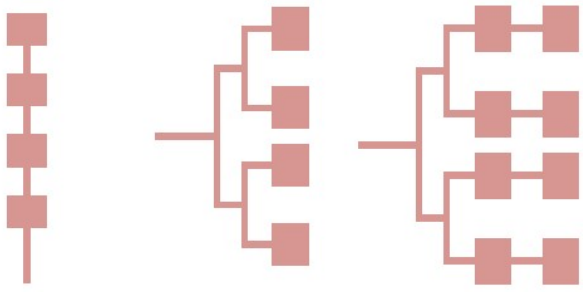
b) Corporate feed network

c) Series-Corporate feed network

2.5.1 Series Feed

A series feed in an antenna array is a type of feed network that connects antenna elements in a series along a feed line. The input signal is fed into the feed network at one end and then coupled to each antenna element in a series.

A series feed network is a type of feeding network that connects antenna elements in an array along a single feeding line. In a series feed network, each antenna element takes power from the feeding line and passes the rest to the next element. A series feed network permits the main beam of the array to be inclined by slightly modifying the frequency.



(a) (b) (c)

Fig. 2.16: (a) Series feed, (b) Corporate feed, (c) Series-corporate feed.

2.5.2 Corporate feed

A corporate feed is a network that distributes power to the elements of an antenna array, allowing for over-amplitude and phase of every component. This technique is often used in microstrip patch antennas, open-end guides, and dipole arrays.

A corporate feed network in an antenna array distributes power to the array's elements using phase shifters to achieve a desired amplitude function. The power is split similarly at separate junctions of the microstrip patch array antenna to ensure uniform distribution.

2.5.3 Series-Corporate Feed

A series-corporate feed within an antenna array integrates both series-fed and corporate-fed array antenna methodologies. The corporate feed plays an important role in the feed circuit, and the power divider is a key part of the corporate feed.

Chapter 3: DESIGN OF A 2×2 ARRAY

3.1 Introduction

The primary goal of this chapter is to create, analyze, and optimize a 2×2 array antenna. For this purpose, a 2×2 array with a both-sided MIC network has been designed, maintaining a variety of distances among patch elements, such as 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, and 0.75λ, both horizontally and vertically. For this objective, a 2×2 array incorporating a both-sided MIC network has been created, preserving a selection of distances between patch elements, such as 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, and 0.75λ, in both horizontal and vertical directions. The Greek letter lambda (λ) is a representation of wavelength in antenna design. A wavelength consists of a sine wave that keeps propagating as it travels through the cosmos and the atmosphere. With the advances in communication networks, a rise in the directivity of wave propagation in free space is required to improve the extent of communication systems. A single antenna produces a signal with a high beam width and less directivity. The solution to this is assembling components arranged in a systematic way by making an array. Thus, the signal beam produced will be more directional than that created by one element at the expense of antenna size. The array's radiation characteristics can be influenced by any of the techniques mentioned below:

1. The layout of the array's shape (linear, planar, circular, or spherical).
2. Inter-space gap among neighboring components.
3. The magnitude of excitation for every individual component.
4. Excitement phase for each distinct component.
5. Radiation pattern of the separate component.

From this technique, the first two techniques are related to my work. A planar array is a flat, two-dimensional arrangement of antennas. The components of a planar array are arranged in a grid with rows and columns. Gain and directivity in this array vary with inter-element spacing. Optimal inter-element spacing of an antenna array to achieve high decorrelation between signals at different elements.

3.2 Design of a Single Antenna

A single antenna is created with Teflon glass fiber functioning as the substrate, which possesses a depth of 0.8 mm and a dielectric constant of 2.15. The substrate has a dielectric loss tangent of 0.001. Copper with a depth of 0.018 mm serves as the conductor on both the emitting plane and the ground plane. This antenna functions at a 10 GHz frequency.

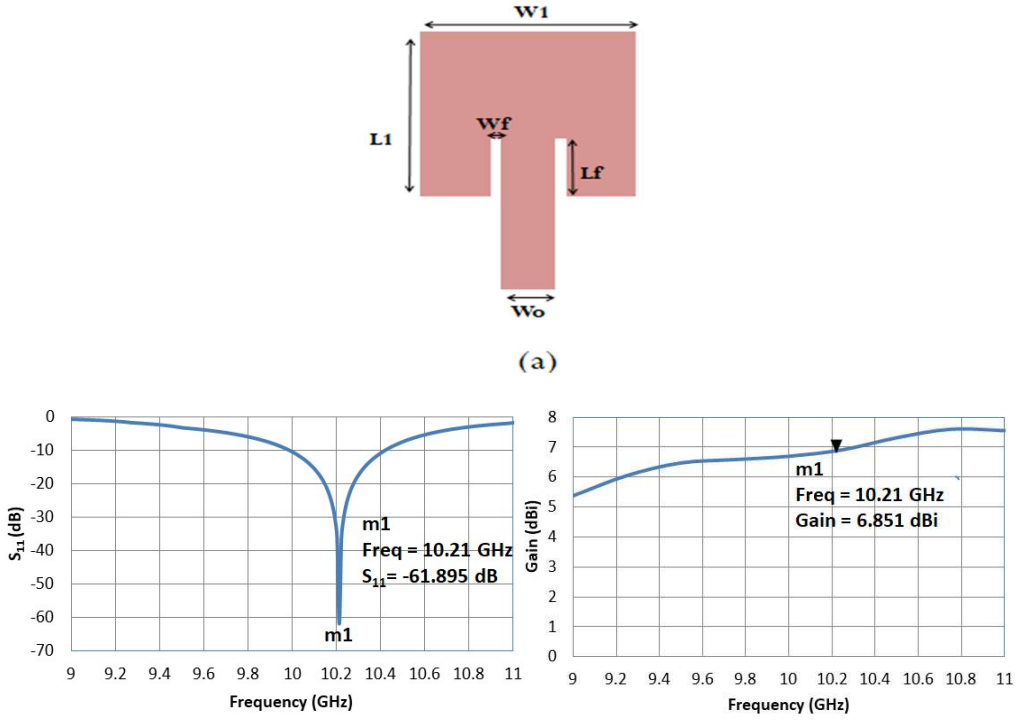


Fig. 3.1: (a) Single element, (b) Reflection coefficient, (c) Gain.

Table-3.1: Geometric values of single-element antenna.

Parameter	Value
W1	9.75 mm
L1	9.75 mm
Wf	3.34 mm
Lf	0.5 mm
W_0	2.4 mm

An inset feed line, having a length of 3.34 mm and a width of 0.5 mm, is designed to improve the reflection coefficient of the antenna. The input impedance of

this antenna is 50 Ω. The width of the transmission line is 2.40 mm. After optimization, the size of the antenna is measured to be 9.75×9.75 mm^2.

The recommended single-element inset feed rectangular microstrip patch array antenna functions at a frequency of 10 GHz, with a reflection coefficient of -61.895 dB, and a gain of 6.585 dBi, as shown in Fig. 3.1.

3.3 Feed Network Design and Performance

The feed network is composed of a microstrip-slot section circuit and a slot-microstrip section circuit. The slot-ring is positioned at the center of the array antenna, with four microstrip lines connected to the slot-ring. The upper layer of the substrate supports the antenna components along with the microstrip line feeding system, while the reverse part features a slot line feeding system. Within the section circuit of the feed system, the microstrip line is initially provided by a microwave source. Following this, parallel in-phase sectioning is executed on the slot line located on the rear side. Afterward, an opposite phase sectioning series is executed from the slot line to the microstrip line located on the upper layer.

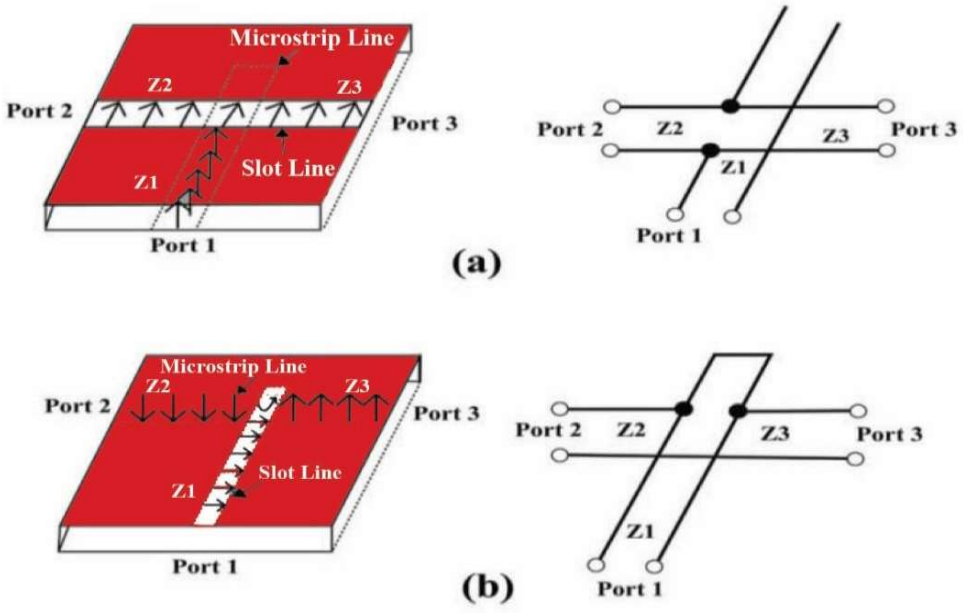


Fig. 3.2: Equivalent circuit of mentioned feed network (a) microstrip-slot section circuit, (b) slot-microstrip section circuit.

In the microstrip-slot section, parallel sectioning is achieved through electromagnetic coupling from the 50-Ω microstrip line on the upper layer to the 100-Ω slot line on the rear side. In the two slot-microstrip sections, series sectioning is conducted from the 100-Ω slot line to the 50-Ω microstrip line.

The equivalent circuit for the section circuits is depicted in Fig. 3.2. The microstrip-slot section circuit is arranged in parallel, and to achieve proper impedance matching, the impedance of the slot line must be twice that of the microstrip line, as depicted in Fig. 3.2(a). In this scenario, two output signals located at an equal distance from the section point on the slot line exhibit the same amplitude and are in phase. Conversely, the slot-microstrip section circuit is connected in series, and the requirement for impedance matching is that the impedance of the microstrip line must be half that of the slot line, as shown in Fig. 3.2 (b). Due to the series coupling, two output signals positioned at the same distance from the section point on the microstrip line have equal amplitude but are 180° out of phase.

. The array's feed network is constructed utilizing two-sided MIC technology to address the impedance matching issues commonly found in traditional feed networks, resulting in enhanced performance. This suggested feed network is characterized by its simplicity and straightforward design process. The array antenna does not necessitate an impedance matching circuit and features a remarkably simple circuit layout, primarily owing to the effective integration of both the microstrip-slot parallel section circuit and the slot-microstrip series section circuit. This array does not require structural changes through stubs, transformers, multi-section transformers, taper lines, inductors, or capacitors. The array antenna, along with its feed circuit, presents a mirror-symmetric configuration that can be realized in a remarkably simple manner. A complex array antenna, due to impedance-matching circuits, can be avoided, uses a feed circuit on both sides, and improves performance.

3.4 Geometry of the 2×2 Array Antenna

The structure is formed by square patches that radiate, paired with a feed network that is constructed by applying both-sided MIC technology. In this chapter, an array with four components has been designed using corporate feed. The

functioning frequency of this four-component array antenna is set at 10 GHz. The upper layer of

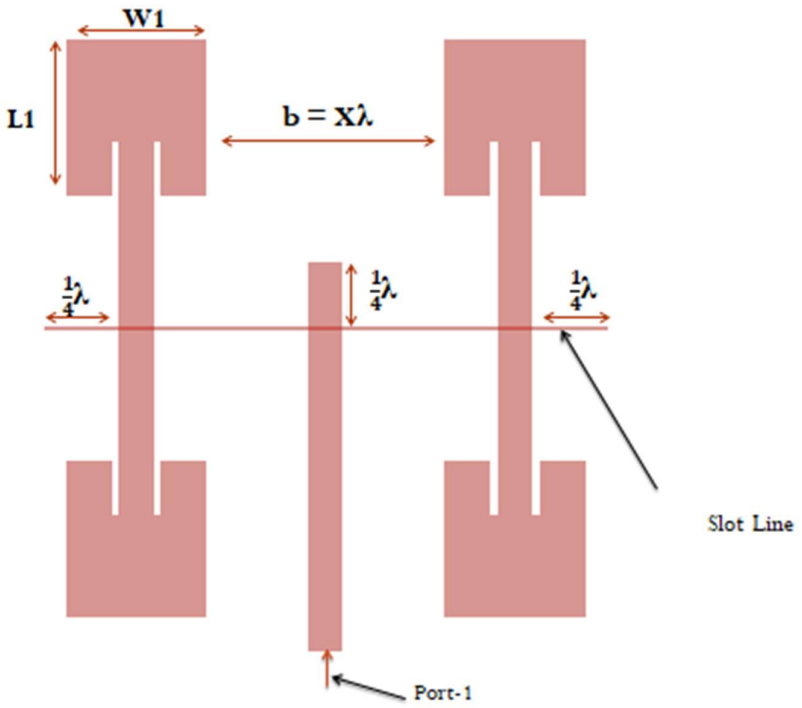


Fig. 3.3: Layout of 2×2 array.

the substrate supports the antenna components and the microstrip line feed system, while the lower layer incorporates a slot line feed system. The size of each square patch is 9.75×9.75 mm2. Microstrip line width and feed length of patch is W_0 = 2.4 mm, Lf = 5.47 mm. Each individual patch component is linearly polarized. The distances amongst patches are kept same, horizontally and vertically. Horizontal and vertical distance between two patches elements is b = xλ (where, x = 0.5, 0.55, 0.6, 0.65, 0.7, 0.75).

The length of the microstrip above the slot line = (1/4)λ. The extension of the slot lines to the left and right of the microstrip line = (1/4)λ. Slot line lengths are 33.43 mm, 34.524 mm, 35.618 mm, 36.712 mm, 37.806 mm and 38.9 mm for 2×2 arrays placed horizontally and vertically with the same spacing (0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ).

There are two categories of section circuits in feed networks: the "Microstrip-Slot section circuit" and the "Slot-Microstrip section circuit". In the Microstrip-Slot section circuit, a microwave source initially feeds the microstrip line. Following this, parallel in-phase sectioning is executed towards the slot line located on the lower part, which involves electromagnetic coupling from the 50 Ω microstrip line situated on the upper layer to the 100 Ω slot line on the lower part. Afterward, at the two Slot-Microstrip sections, series reverse-phase sectioning is performed from the 100 Ω slot line to the 50 Ω microstrip line on the upper layer. Therefore, there is no requirement for an impedance-matching transmission line within the feed circuit.

In this setup, the polarization component that is orthogonal to the electric field is emitted by each of the antenna elements. This setup comprises strip lines and slot lines arranged in perpendicular directions to prevent the generation of any unwanted cross-polarization component. At the Slot-Microstrip section, the signal is split into equal amplitudes but with opposing phases. By positioning the radiating elements at equal distances from the section point, the excitation modes of all radiating elements can be maintained in the identical phase, ensuring that the array exhibits mirror symmetry relative to the slot line. Consequently, the arrangement of the radiating elements is symmetrical within the E-plane.

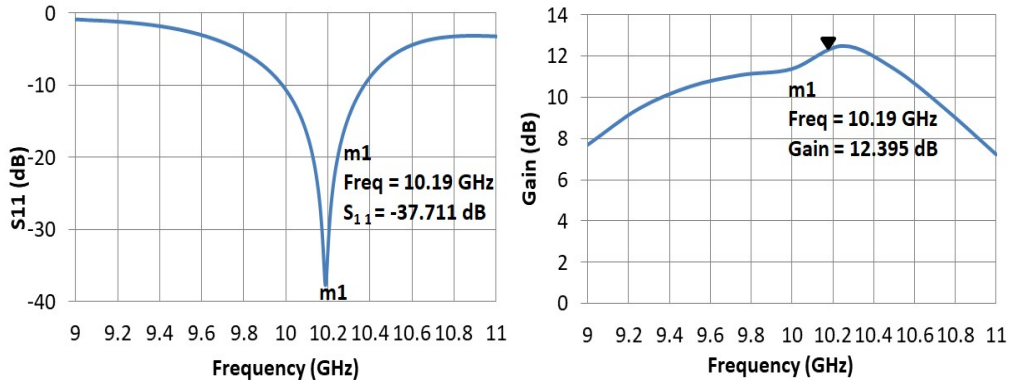
3.5 Parametric Analysis

A parametric assessment is carried out to improve the antenna's parameters. It allows us to assess the influence of diverse parameters on impedance, bandwidth, gain, directivity, reflection coefficient, axial ratio, and radiation pattern. Furthermore, this analysis offers insights into antenna characteristics that assist in optimizing the antenna for optimal performance. For this reason, the effects of adjusting the microstrip line width (MW) and the slot line width (SW) are investigated. Additionally, the separation between the microstrip-slot junction and the slot-microstrip junction is also recognized. During the process of parametric analysis, all parameters except for the ones of interest remain unchanged.

The spacing among components in the array is done so that they are not very close to one another, which helps to reduce the mutual coupling between the components. From parametric analysis, optimized values are taken for designing a 2×2 array, maintaining a variety of distances among patch elements, i.e., 0.5λ, 0.55λ, 0.6λ, 0.65λ,

0.7λ, and 0.75λ, both horizontally and vertically. After that, antenna performance is observed. The simulation of antenna performance is done with the Advanced Design System (ADS) 2022.

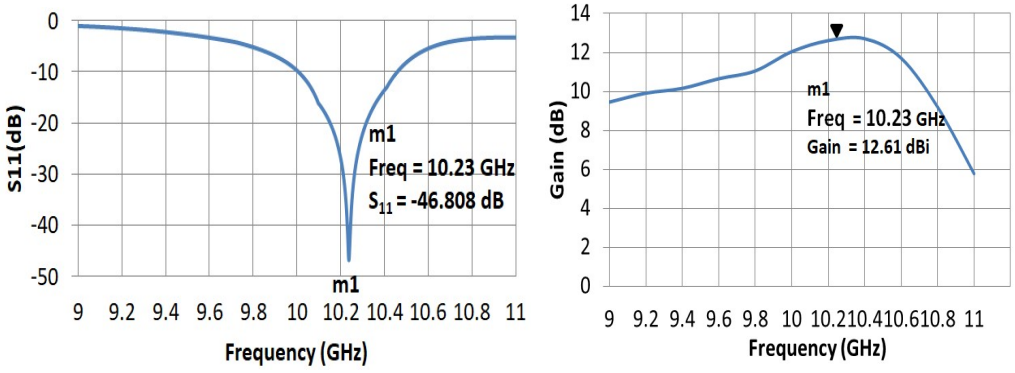
For instance, for a distance of 0.5λ between 4 patches horizontally and vertically, the 2×2 array results in a reflection coefficient S11 = -37.711 dB and a gain of 12.395 dBi.



(a) (b)

Fig. 3.4.1: 2×2 array (0.5λ) (a) Reflection Coefficient, (b) Gain.

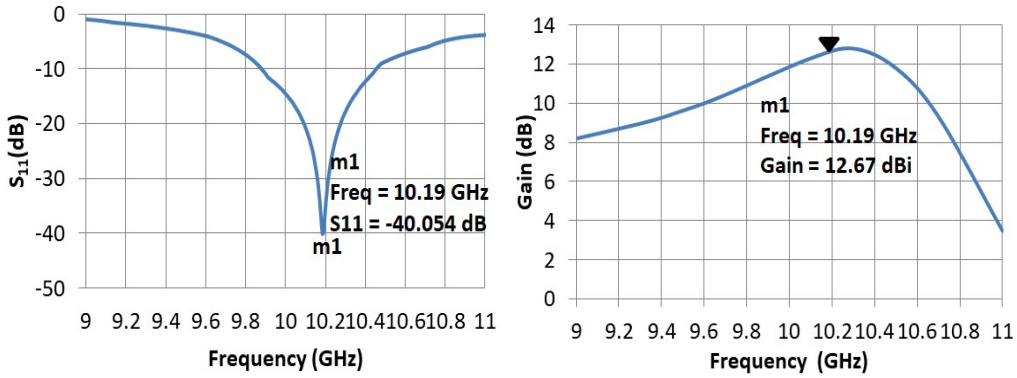
For instance, for a distance of 0.55λ among 4 patches horizontally and vertically, the 2×2 array results in a reflection coefficient S_{11} = -46.808 dB and Gain = 12.61 dBi.



(a) (b)

Fig. 3.4.2: 2×2 array (0.55λ) (a) Reflection Coefficient, (b) Gain.

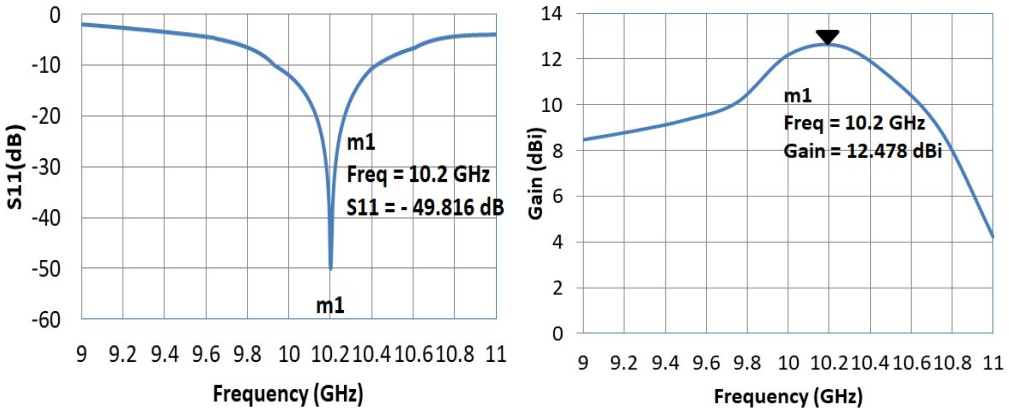
For instance, for a distance of 0.6λ among 4 patches horizontally and vertically, the 2×2 array results in a reflection coefficient S_{11} = -40.054 dB and Gain = 12.67 dBi.



(a) (b)

Fig. 3.4.3: 2×2 array (0.6λ) (a) Reflection Coefficient, (b) Gain.

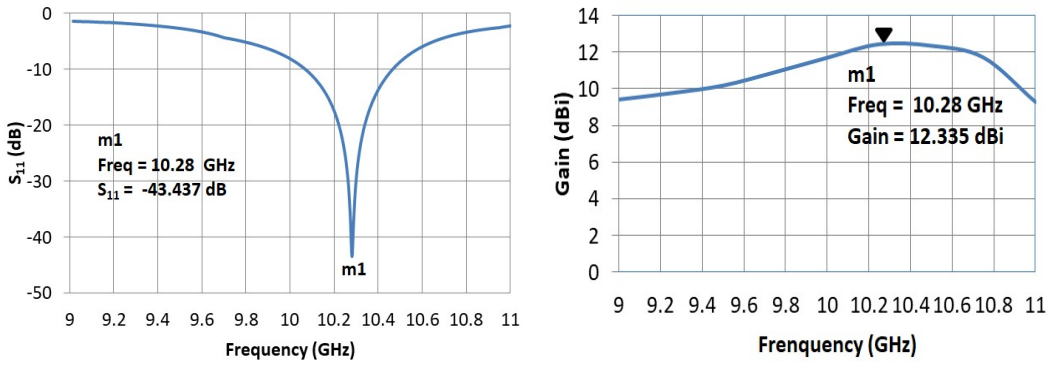
For a distance of 0.65λ among 4 patches horizontally and vertically, the array results in a reflection coefficient S_{11} = -49.816 dB and gain = 12.478 dBi.



(a) (b)

Fig. 3.4.4: 2×2 array (0.65λ) (a) Reflection Coefficient, (b) Gain.

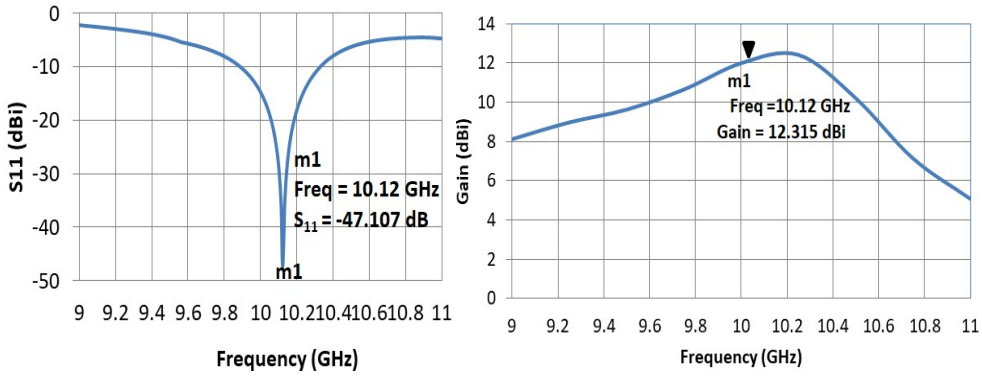
For a distance of 0.7λ among 4 patches horizontally and vertically, the array results in Reflection Coefficient S_{11} = -43.437 dB and Gain = 12.335 dBi.



(a) (b)

Fig. 3.4.5: 2×2 array (0.7λ) (a) Reflection Coefficient, (b) Gain.

For a distance of 0.75λ among 4 patches horizontally and vertically, the array results in a reflection coefficient S_{11} = -47.107 dB and gain = 12.315 dBi.



(a) (b)

Fig. 3.4.6: 2×2 array (0.75λ) (a) Reflection Coefficient, (b) Gain.

From graph analysis, it is seen that distance affects the gain and reflection coefficient. It is important to minimize the mutual linkage between the elements.

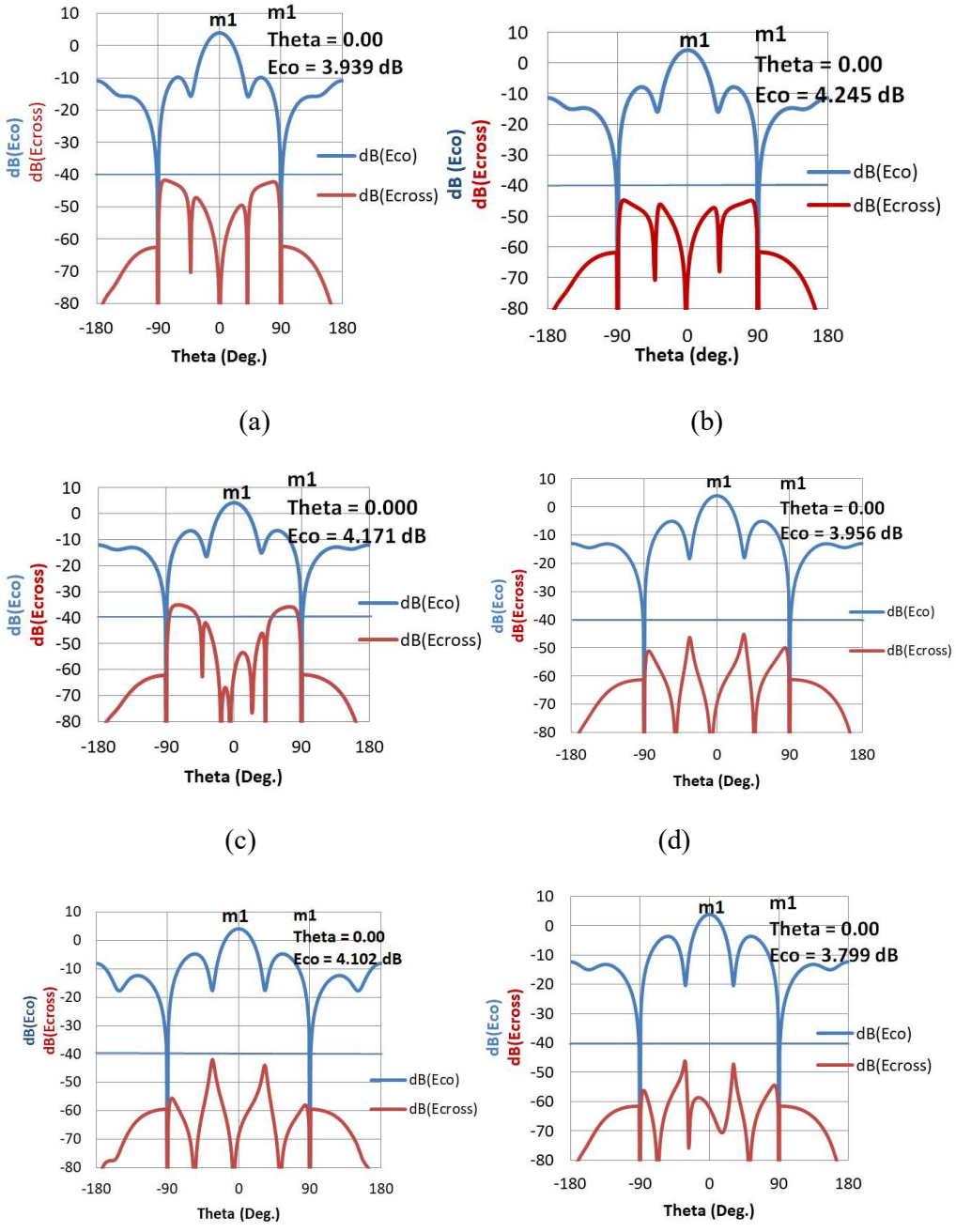


Fig. 3.5: Eco and Cross of (a) 2×2 array (0.5λ), (b) 2×2 array (0.55λ), (c) 2×2 array (0.6λ), (d) 2×2 array (0.65λ), (e) 2×2 array (0.7λ), (f) 2×2 array (0.75λ).

From Fig. 4.2 (a), (b), (c), (d), (e), (f), the eco value of 2×2 array (0.5λ) = 3.939 dB, the eco value of 2×2 array (0.55λ) = 4.245 dB, the eco value of 2×2 array (0.6λ)

= 4.171 dB, the eco value of 2×2 array (0.65λ) = 3.956 dB, the eco value of 2×2 array (0.7λ) = 4.102 dB, the eco value of 2×2 array (0.75λ) = 3.799 dB. By adjusting the space between the patches, the optimized eco value is obtained. The optimized eco value is obtained from the distance between the patches of 0.55λ.

The 3D radiation pattern is exhibited in Fig.3.6. The radiation changes with distance between patches and the 2×2 array (0.55λ) has lower side lobe and better 3D radiation pattern than others.

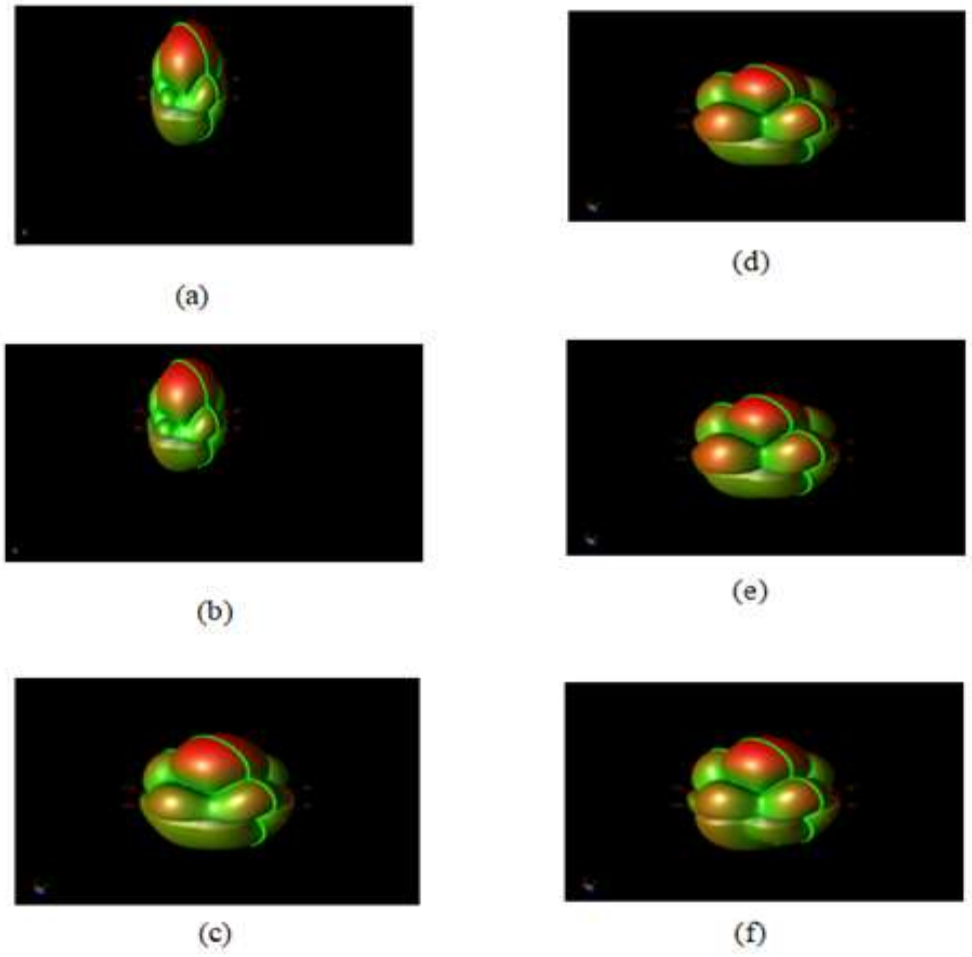


Fig. 3.6: 3D Radiation Pattern for 2×2 array (a) 0.5λ, (b) 0.55λ, (c) 0.6λ, (d) 0.65λ, (e) 0.7λ, (f) 0.75λ.

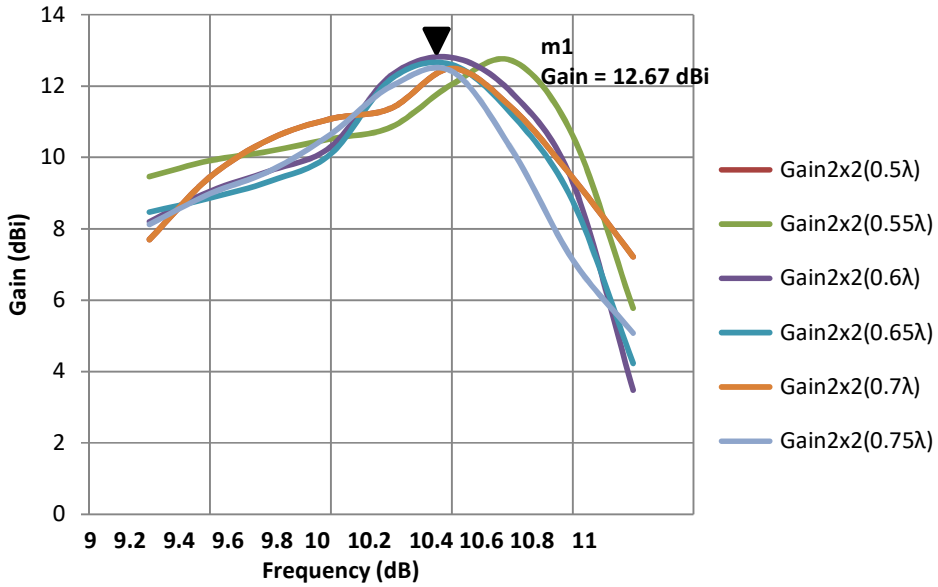


Fig. 3.7: Gain comparison graph of 2×2 array.

3.6 Results and Discussion

From graph analysis, it is seen highest gain (12.67 dBi) occurs in a 2×2 array (0.6λ).

It is observed from data analysis that a 2×2 array (0.6λ element spacing) has better gain (12.67 dBi) than others.

Table-3.2: shows the gain of a 2×2 array (distance kept the same among patches horizontally and vertically).

Distance between patches horizontally and vertically	Gain (dBi)
0.5λ	12.395
0.55λ	12.610
0.6λ	12.670
0.65λ	12.478
0.7λ	12.335
0.75λ	12.315

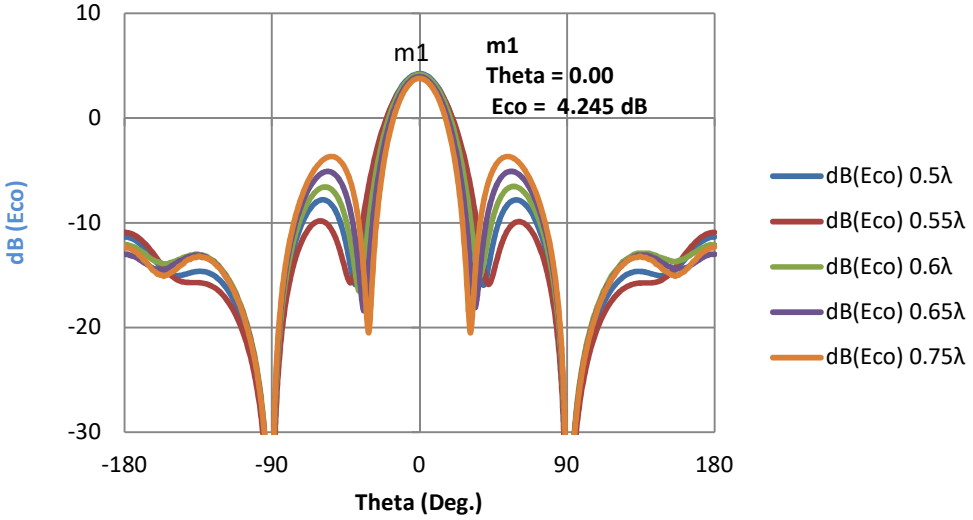


Fig. 3.8: Comparison Eco value of 2×2 array (0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ).

Table-3.3: shows Eco value of a 2×2 array.

Distance between patches horizontally and vertically	dB (Eco)
0.5λ	3.939
0.55λ	4.245
0.6λ	4.171
0.65λ	3.956
0.7λ	4.102
0.75λ	3.799

From Table-3.3, the 2×2 array (0.55λ element spacing) has the highest eco (4.245 dB) among the six arrays.

From the simulation results, it is noticeable that the values of gain, directivity, and eco increase from a single-element antenna to a 4-element square microstrip patch antenna. This affirms that array antennas achieve superior gain and directivity, which may help to mitigate the effects of high free-space path loss in millimeter-wave. The distance between neighboring elements in the array antenna is established correctly, ensuring they are not positioned too closely, which serves to diminish mutual coupling. With corporate feed, the antenna performance improves in terms of gain and directivity.

The various parameters of an antenna array, such as gain, reflection coefficient and radiation pattern, eco are analyzed. Distances of 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, and 0.75λ among the 4 patches are kept the same horizontally and vertically. After that, the performing of the antenna is monitored. From the simulation results, it is seen that the array with 0.6λ distance has higher gain and 0.55λ distance has higher eco. For the purpose of simulation, software named “Path Wave Advanced Design System (ADS) 2022” has been used.

Chapter 4: DESIGN OF A COMPACT 2×4 MICROSTRIP ARRAY ANTENNA WITH SERIES-CORPORATE FEED USING BOTH-SIDED MIC NETWORK

4.1 Introduction

The key purpose of this project is to design, analyze, and optimize a 2×4 array antenna**.** For this purpose, a 2×2 array with both-sided MIC network has been designed maintaining a variety of distances among patch elements, such as 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ and 0.75λ, both horizontally and vertically. Next, a 2×4 array with series-corporate feed is created by adding four components to a 2×2 array using series feed. With the advances in communication systems, there is a necessity for enhanced of wave propagation in free space is required to extend the extent of communication systems. Single antenna produces signal with high beam width and less directivity. The answer to this issue is to arrange components systematically by forming an array. Thus, the signal beam generated will possess more directivity than that created by a single element, which necessitates a larger antenna size.

4.2 Geometry of the 2×4 Array Antenna

Through parametric analysis, patch elements of dimension (11.75×11.75 mm^2) are selected. Adding 4 patch elements (with series feed) in addition to a 2×2 array with corporate feeding produces a 2×4 array with corporate-series feed. Through parametric analysis, the optimized vertical distance is chosen to be 9.75 mm. Therefore, the vertical distance, e = 9.75 mm, is the same for the 2×4 array (with a 2×2 array the distance is 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ between the 4 patches horizontally and vertically). Microstrip line width of all patch elements is W_0 = 2.4 mm. The length of the microstrip above the slot line = 1/4 λ. The extension of the slot lines to the left and right of the microstrip line = 1/4 λ. Slot line lengths are 33.43 mm, 34.524 mm, 35.618 mm, 36.712 mm, 37.806 mm, and 38.9 mm for 2×4 array (with 2×2 array placed horizontally and vertically with the same spacing 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ).

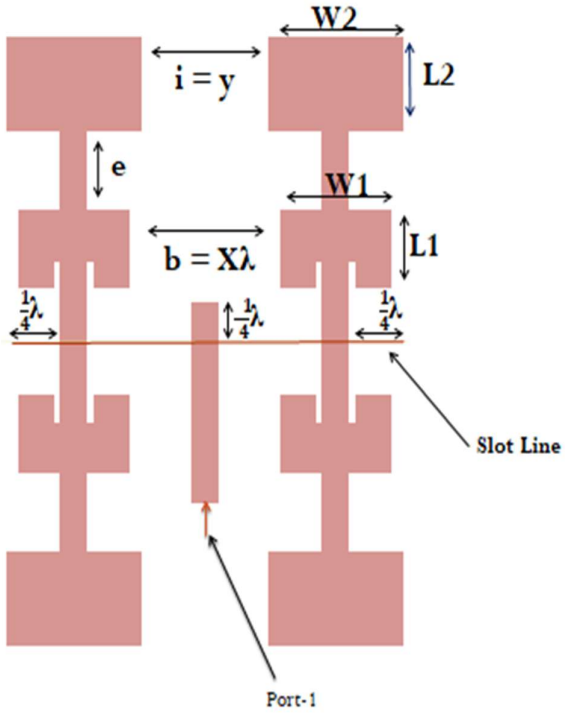


Fig. 4.1: Dimensions of 2×4 array (includes 2×2 array with horizontal and vertical 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ spacing).

Table-4.1: Geometric values of 2×4 array antenna.

Parameter	Value
W2	11.75 mm
L2	11.75 mm
e	9.75 mm
W1	9.75 mm
L1	9.75 mm

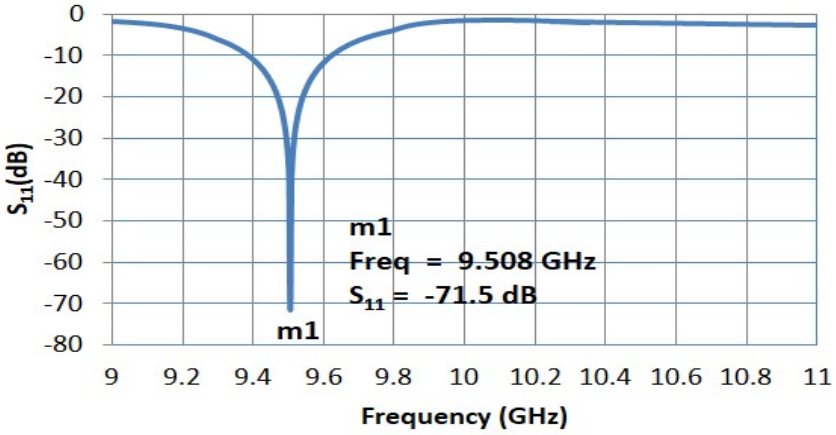
4.3 Parametric Analysis

A parametric analysis is run to enhance the values of the 2×4 array antenna parameters. It allows for the analysis of the effects of diverse parameters on impedance, bandwidth, gain, directivity, reflection coefficient, axial ratio, and radiation pattern. Furthermore, this analysis offers insights into antenna characteristics that assist in optimizing the antenna for optimal performance. For that purpose, the impacts of adjusting the microstrip line width (MW) and the slot line width (SW) are explored. Besides, the distance between the microstrip-slot section point and the slot-microstrip section point is also observed. Throughout the parametric analysis, the parameters not of interest are held constant, while the parameters of interest are varied.

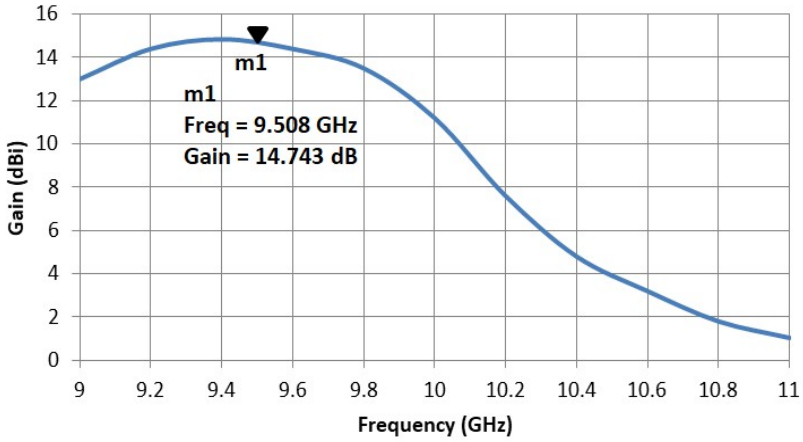
The vertical distance between patch (9.75×9.75 mm^2) and patch (11.75×11.75 mm^2) is derived by parametric analysis.

The spacing among components in the array is done so that they are not very close to each other, which assists in reducing the mutual coupling among the elements. After that, the simulation is done, and antenna performance is observed. The simulation of antenna performance is done with simulation software named Path Wave Advanced Design System (ADS).

For a 2×4 array (including a 2×2 array with 0.5λ spacing between 4 patches horizontally and vertically), the results show reflection coefficient S_{11} = -71.5 dB and gain = 14.743 dBi.



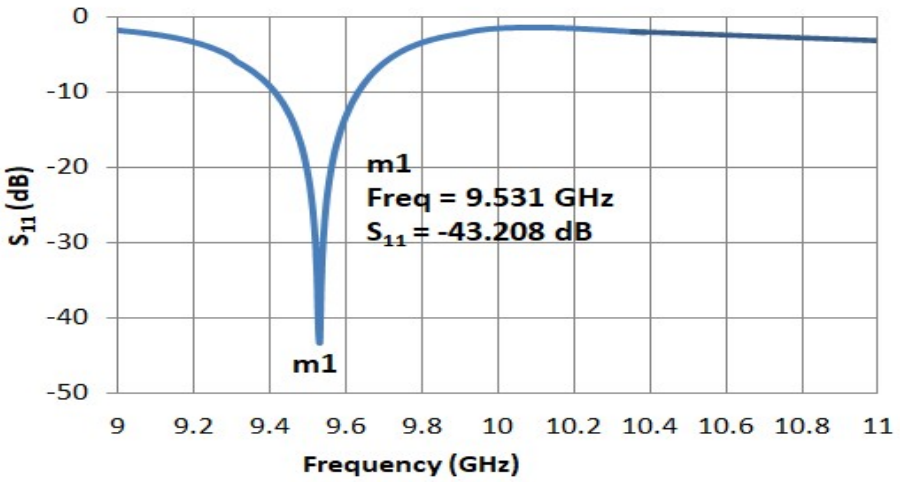
(a)



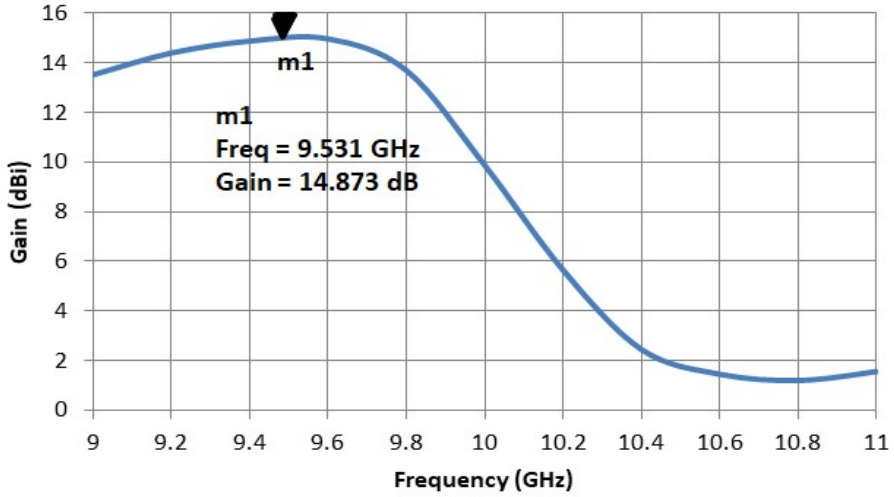
(b)

Fig. 4.1.1: 2×4 array 0.5λ (a) Reflection Coefficient, (b) Gain.

For a 2×4 array (including a 2×2 array with 0.55λ spacing between 4 patches horizontally and vertically), the results show reflection coefficient S_{11} = -43.208 dB and gain = 14.873 dBi.



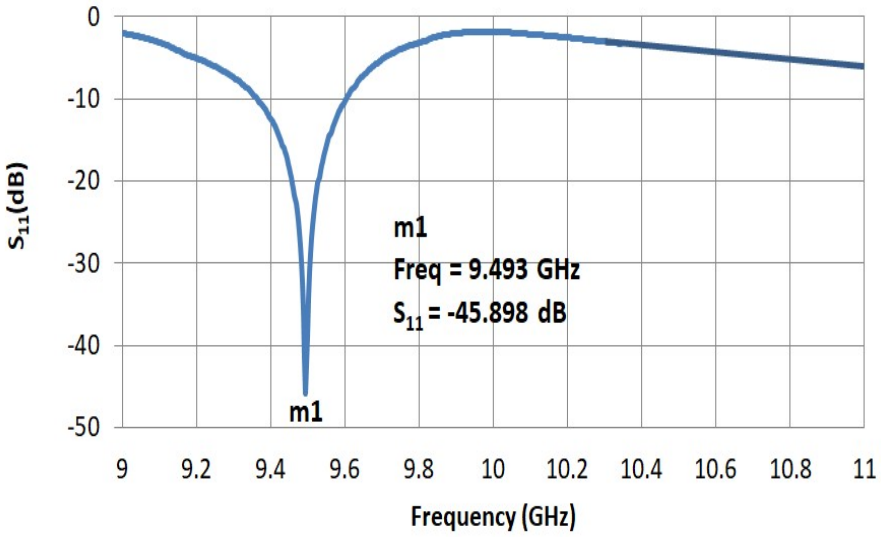
(a)



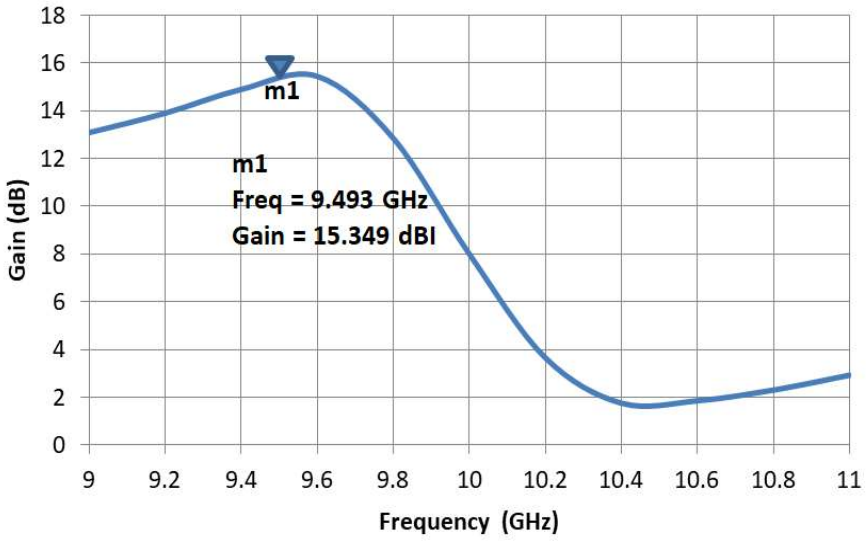
(b)

Fig. 4.1.2: 2×4 array 0.55λ (a) Reflection Coefficient, (b) Gain.

For a 2×4 array (including a 2×2 array with 0.6λ spacing between 4 patches horizontally and vertically), the results show reflection coefficient S_{11} = -45.898 dB and gain = 15.349 dBi.



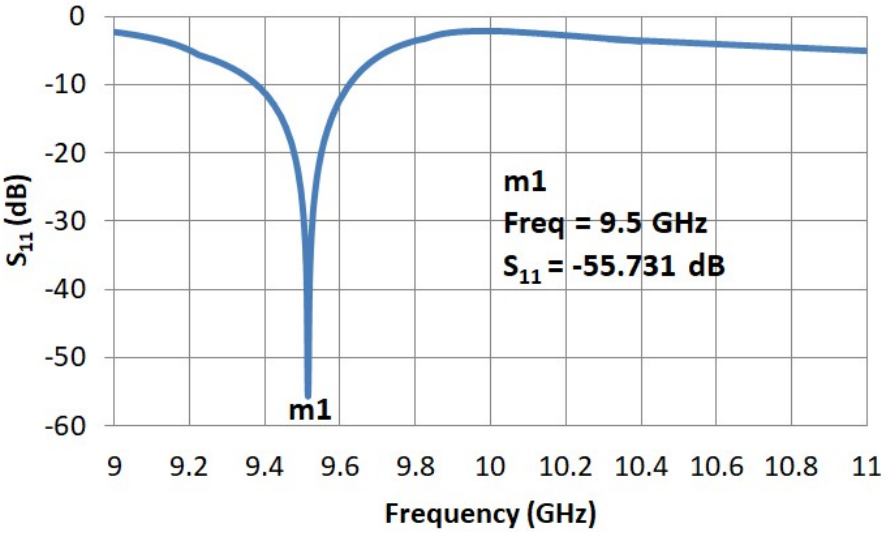
(a)



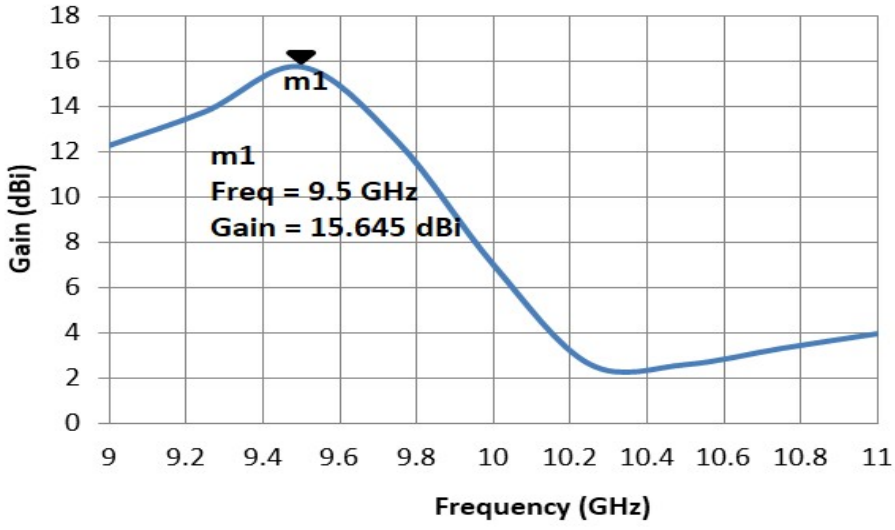
(b)

Fig. 4.1.3: 2×4 array 0.6λ (a) Reflection Coefficient, (b) Gain.

For a 2×4 array (including a 2×2 array with 0.65λ spacing between 4 patches horizontally and vertically), the results show reflection coefficient S_{11} = -55.731 dB and gain = 15.645 dBi.



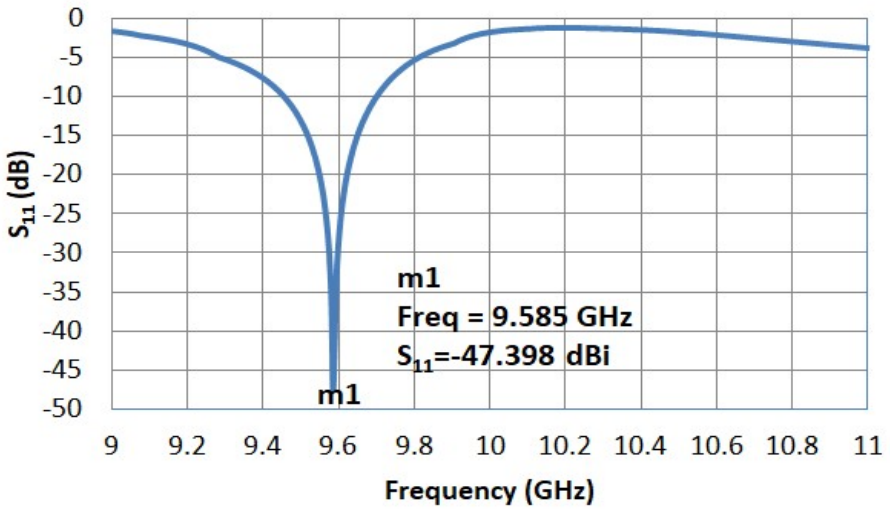
(a)



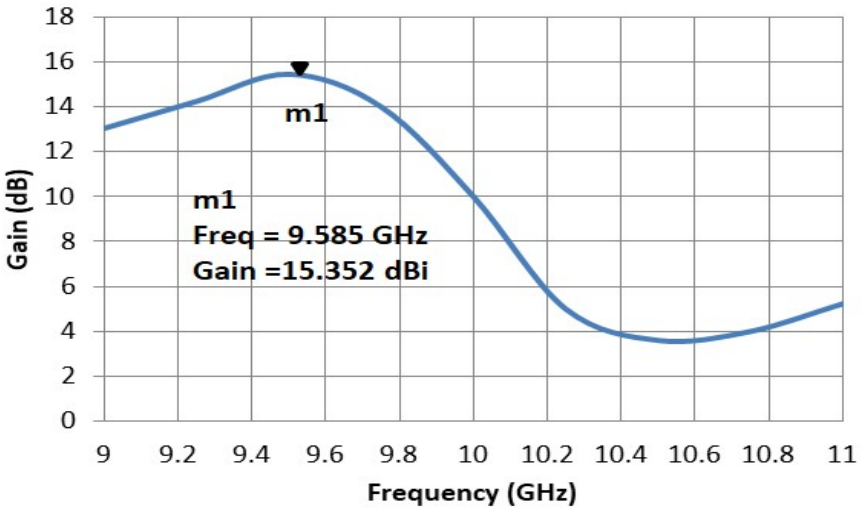
(b)

Fig. 4.1.4: 2×4 array 0.65λ (a) Reflection Coefficient, (b) Gain.

For a 2×4 array (including a 2×2 array with 0.7λ spacing between 4 patches horizontally and vertically), the results show Reflection Coefficient S_{11} = -47.398 dB and Gain = 15.352 dBi.



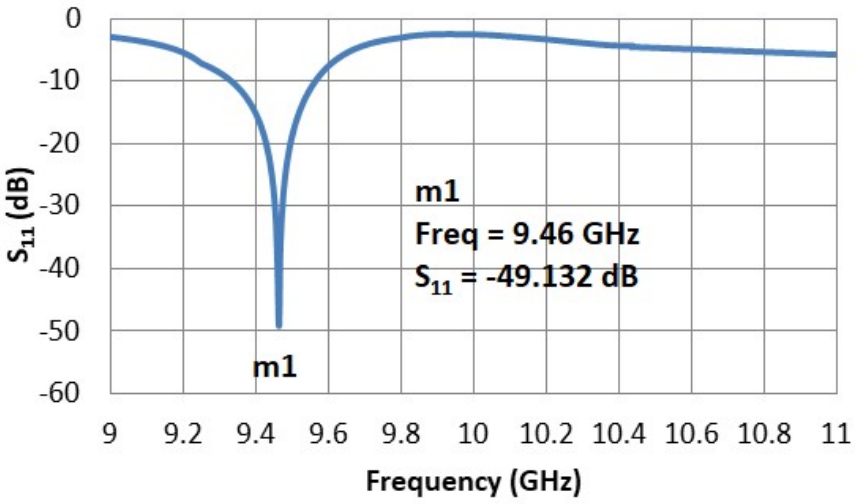
(a)



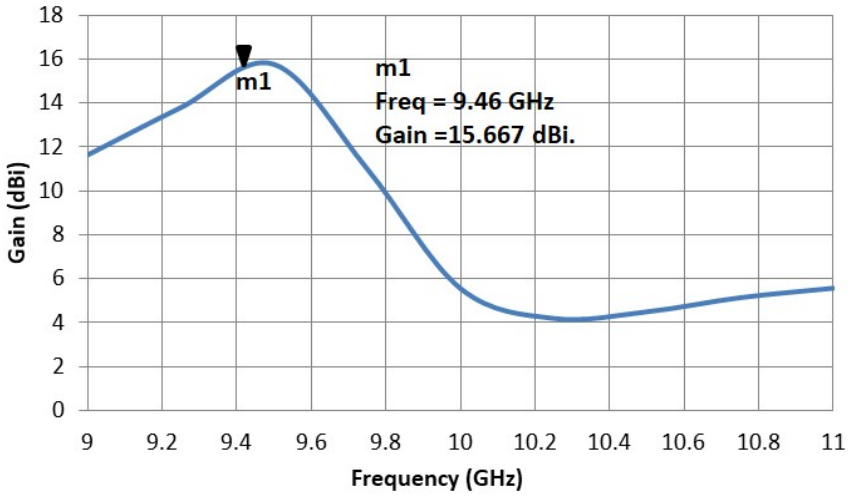
(b)

Fig. 4.1.5: 2×4 array 0.7λ (a) Reflection Coefficient, (b) Gain.

For a 2×4 array (including a 2×2 array with 0.75λ spacing between 4 patches horizontally and vertically), the results show reflection coefficient S_{11} = - 49.132 dB and gain = 15.667 dBi.



(a)



(b)

Fig. 4.1.6: 2×4 array 0.75λ (a) Reflection Coefficient, (b) Gain.

From the graph analysis, the effect of distance on gain and reflection coefficient can be seen. Therefore, optimized distance is important to suppress mutual coupling between elements.

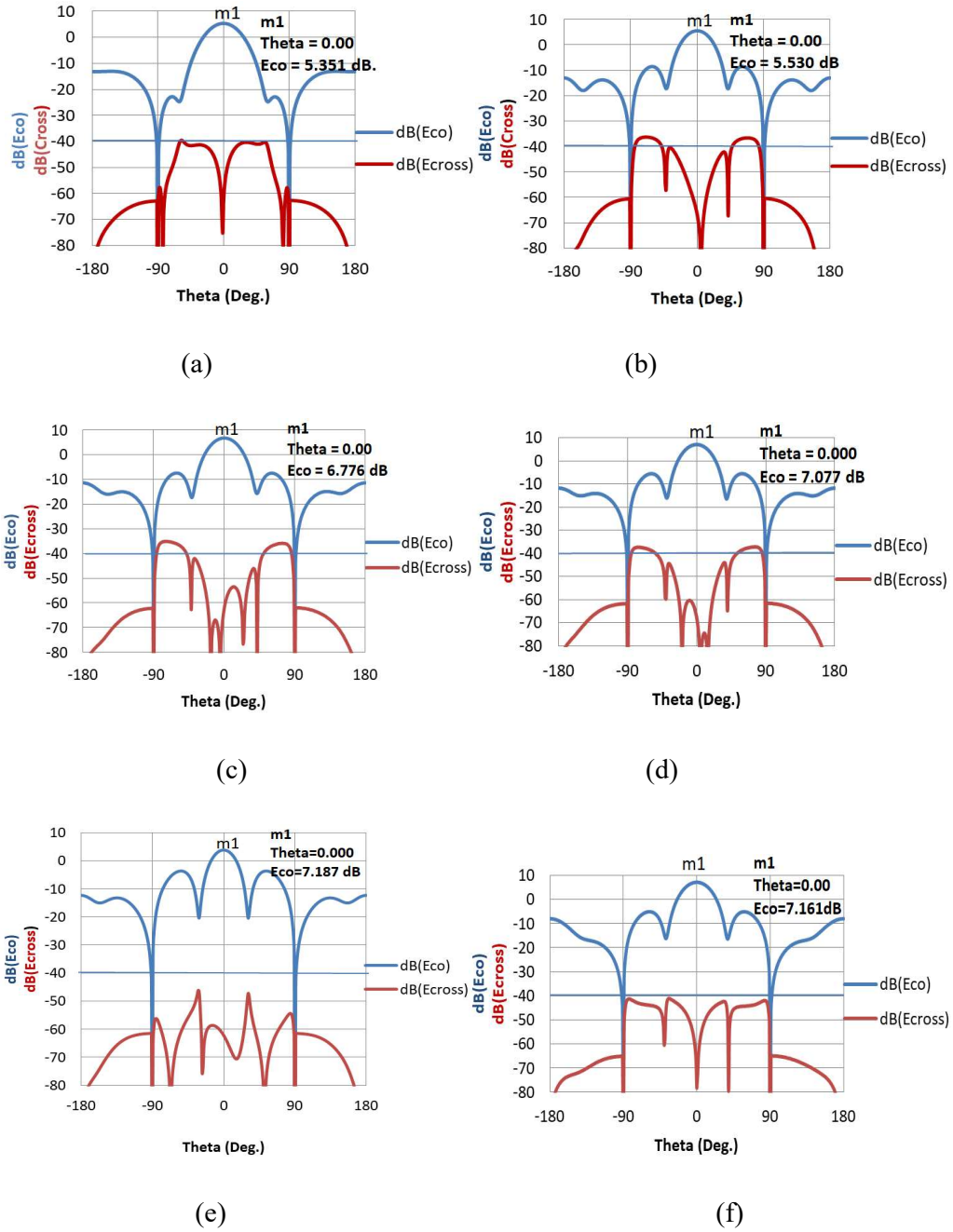


Fig. 4.2: Eco and cross of 2×4 array (a) 0.5λ, (b) 0.55λ, (c) 0.6λ, (d) 0.65λ, (e) 0.7λ, (f) 0.75λ.

From Fig. 4.2 (a), (b), (c), (d), (e), (f), the eco value of 2×4 array (0.5λ) = 5.351 dB, the eco value of 2×4 array (0.55λ) = 5.530 dB, the eco value of 2×4 array (0.6λ) = 6.776 dB, the eco value of 2×4 array (0.65λ) = 7.077 dB, the eco value of 2×4 array (0.7λ) = 7.187 dB, the eco value of 2×4 array (0.75λ) = 7.161 dB. By changing the distance between the patches, different eco values are obtained. The optimized eco value is obtained from a distance of 0.7λ between the patches.

Analysis of Fig. 4.3 shows that the 2×4 array (0.7λ) has higher side lobe reduction and better 3D radiation pattern than the other.

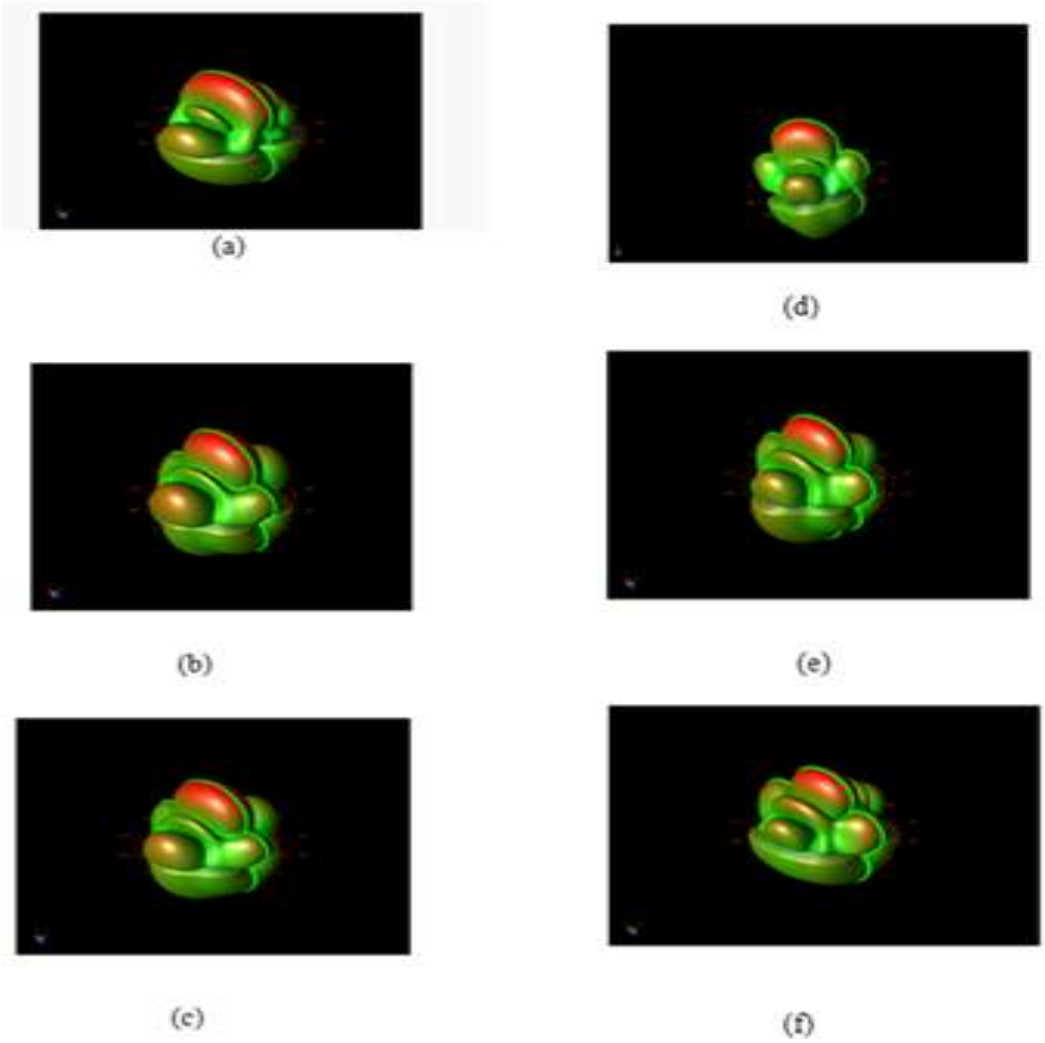


Fig. 4.3: 3D Radiation pattern of (a) 2×4 array 0.5λ, (b) 2×4 array 0.55λ, (c) 2×4 array 0.6λ, (d) 2×4 array 0.65λ, (e) 2×4 array 0.7λ, (f) 2×4 array 0.75 λ.

4.4 Results and Discussion

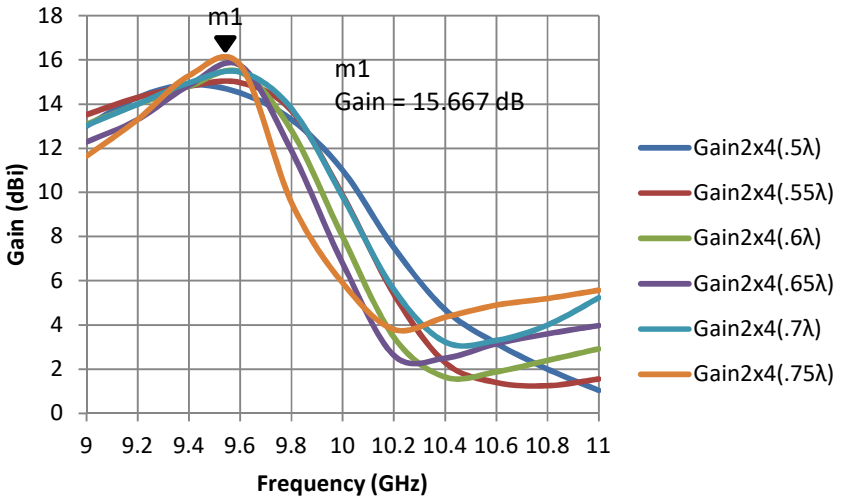


Fig. 4.4: Gain comparison graph of 2×4 array.

From graph analysis, it is seen highest gain (15.667 dBi) occurs in a 2×4 array (0.75λ).

Table-4.2: Values (Reflection Coefficient, Gain) of a 2×4 array.

Parameters	**2×4 array (including 2×2 array with distance of 0.5λ among 4 patches horizontally and vertically)**	**2×4 array (including 2×2 array with distance of 0.55λ among 4 patches horizontally and vertically)**	**2×4 array (including 2×2 array with distance of 0.6λ among 4 patches horizontally and vertically)**	**2×4 array(including 2×2 array with distance of 0.65λ among 4 patches horizontally and vertically)**	**2×4 array (including 2×2 array with distance of 0.7λ among 4 patches horizontally and vertically)**	**2×4 array (including 2×2 array with distance of 0.75λ among 4 patches horizontally and vertically)**
Reflection Coefficient (dB)	-71.5	-43.208	-45.898	-55.731	-47.398	-49.132
Gain (dBi)	14.743	14.873	15.349	15.645	15.352	15.667

Table-4.3: Compare between a single-element antenna, a 2×2 array antenna, and a 2×4 array antenna.

Parameters	Reflection Coefficient (dB)	Gain (dBi)
Single element	-61.895	6.585
2×2 array with a distance of 0.5λ among 4 patches horizontally and vertically	-37.711	12.395
2×2 array with a distance of 0.55λ among 4 patches horizontally and vertically	-46.808	12.610
2×2 array with a distance of 0.6λ among 4 patches horizontally and vertically	-40.054	12.670
2×2 array with a distance of 0.65λ among 4 patches horizontally and vertically	-49.816	12.478
2×2 array with a distance of 0.7λ among 4 patches horizontally and vertically	-43.437	12.335
2×2 array with a distance of 0.75λ among 4 patches horizontally and vertically	-47.107	12.315
2×4 array (including 2×2 array with distance of 0.5λ among 4 patches horizontally and vertically)	-71.5	14.743
2×4 array (including 2×2 array with distance of 0.55λ among 4 patches horizontally and vertically)	-43.208	14.873
2×4 array (including 2×2 array with distance of 0.6λ among 4 patches horizontally and vertically)	-45.898	15.349
2×4 array (including 2×2 array with distance of 0.65λ among 4 patches horizontally and vertically)	-55.731	15.645
2×4 array (including 2×2 array with distance of 0.7λ among 4 patches horizontally and vertically)	-47.398	15.352
2×4 array (including 2×2 array with distance of 0.75λ among 4 patches horizontally and vertically)	-49.132	15.667

Table 4.3 shows that, among the 3 types of antennas, the 2×4 array antenna with 0.75λ has the highest gain of 15.667 dBi.

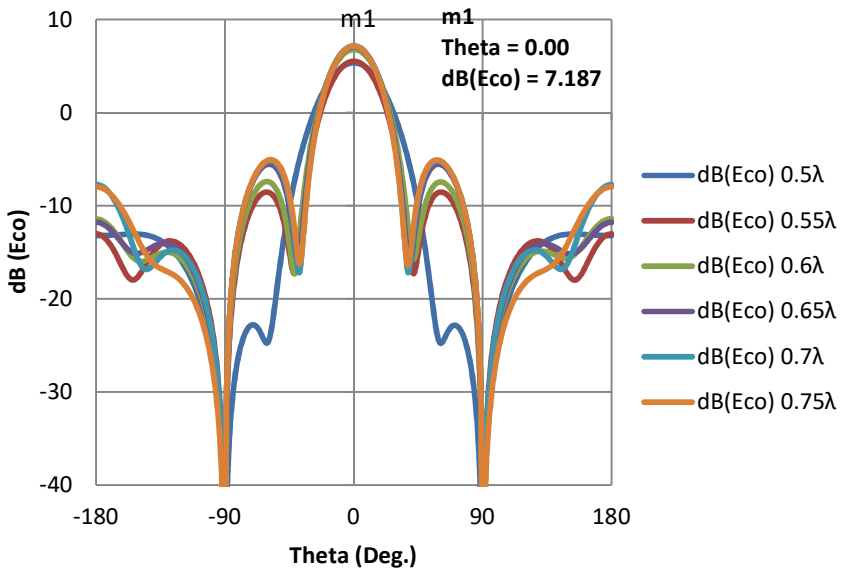


Fig. 4.5: Comparison Eco value of 2×4 array (0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ).

Table-4.4: Comparison of Eco values of 2×2 array and 2×4 array

Antenna	dB (Eco)	Antenna	dB (Eco)
2×2 array(0.5λ)	3.939	2×4 array (0.5λ)	5.351
2×2 array(0.5λ)	4.245	2×4 array (0.55λ)	5.530
2×2 array(0.6λ)	4.171	2×4 array (0.6λ)	6.776
2×2 array(0.65λ)	3.956	2×4 array (0.65λ)	7.077
2×2 array(0.7λ)	4.102	2×4 array (0.7λ)	7.187
2×2 array(0.75λ)	3.799	2×4 array(0.75λ)	7.161

From Table-4.4 it can be seen that the eco value increases from a 2×2 array to 2×4 array.

The distance among the patch elements affects the antenna gain, directivity, and eco value. Data analysis showed that a 2×4 array with 0.75λ patch spacing provides the highest gain of 15.667dBi, and a 2×4 array with 0.7λ patch spacing provides the highest Eco (7.187dB).

From the simulation findings, it is evident that both gain, and directivity increase when transitioning from a single-component antenna to an 8-component array antenna. This confirms the fact that an array antenna propagates higher gain and directivity, which can surpass the difficulties posed by significant free-space path loss at millimeter-wave frequencies. The spacing between elements in the array is done so that they are not very close to each other, this assists in reducing the mutual coupling among the elements. Different parameters of the antenna array, such as return loss, gain, radiation pattern, and eco are observed. Performance improvement usually occurs with an increase in array elements. For instance, a decrease in side lobe and an increase in gain occur in 2×4 arrays compared to 2×2 arrays.

Therefore, this new antenna will be able to contribute to wireless communication. The array antenna has been proposed for many years. By optimizing and characterizing the antenna parameters, overall gain and eco can be increased, and side lobes can be reduced.

This project has shown simulation analysis using Advanced Design System (ADS), which evaluates performance parameters, such as gain, impedance behavior, and S-parameters for radar, medical, and mobile application environments.

Chapter 5: Conclusion

5.1 Introduction

Antenna arrays, which consist of many radiating elements, are capable of increasing gain, improving directivity, and the ability to electronically steering the radiation pattern. These characteristics make antenna arrays crucial for various applications like radar, wireless communication, radio astronomy, and medical imaging.

Microstrip arrays have been broadly applied in current years because of their vigorous design, light weight, little cost, less profile antenna, planar surfaces, compactness, small size, easy portability, and MMIC design technique. They have some interesting features that are useful in some important applications. They are used in private communication systems, communications through mobile satellite technology, health applications, armed systems (rockets, aircraft, missiles, radio navigation systems, airborne radars), and wireless local area networks (WLAN).

At present, antennas using planar arrays are very important because they can be easily embedded in portable devices, such as laptops, mobile phones, etc.

5.2 Summary

With the large expansion of telecommunications, the create of compact antennas with improved performance and high productivity has become a necessity. In this project, a 2×4 array will be designed that meets some requirements, such as high gain and directivity, reduced the mutual interaction among components.

In this task, a compact microstrip array antenna with a series-corporate feed and, both-sided MIC network is planned. Incorporated both-sided MIC in the create of the array antenna for easy impedance matching. By using an inset feed in patches, the array size is reduced. Better value of gain, directivity, and reflection coefficient will come in this array. The distance between patches suppresses the mutual coupling among the elements, spacing among elements in the array is not very close to each other. An array suppresses side lobes by increasing elements. This configuration contains of strip lines and slot lines in the perpendicular route so that the undesirable cross-polarization element is not create.

A 2×4 array framework is composed of emitting square patches, featuring a feed network developed through both-sided MIC technology. The upper layer of the substrate features the antenna components along with the microstrip line feeding system, while the underside incorporates a slot line feeding system. There are two categories of section circuits within feed networks. Microstrip-slot section circuit and slot-microstrip section circuit. In the microstrip-slot section circuit, parallel sectioning is achieved through electromagnetic coupling, transferring from the microstrip line (50 Ω) located on the upper layer to the slot line (100 Ω) situated on the lower layer. A series sectioning is carried out between the two slot-microstrip branches, from the slot line (100 Ω) to the microstrip line (50 Ω) on the lower side.

In this project, a 2×2 array with 4 elements is added with corporate feeding. 2×4 array with 8 elements connected in series-corporate feeding. It has the advantages of both series feed and corporate feed. A parametric reading is undertaken to refine the characteristics of the antenna. The impact of changing the breadth of the microstrip line and the width of the slot line is examined, and then the optimized values are taken.

The separation between the microstrip-slot section point and the slot-microstrip section point is also noted to identify the features of the antenna. In the course of the parametric analysis, all parameters, aside from those of interest, are maintained at constant values.

Parametric analysis presents the impacts of patch spacing on gain. Based on the analysis of the graph, it is observed that by adjusting the horizontal and vertical separations between the patches of the 2×2 array to 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, and 0.75λ, the highest gain of 12.67 dBi is achieved at 0.6λ within the 2×2 array. Based on the analysis of the graph, it is observed that by adjusting the horizontal and vertical distances within the patches of the 2×4 array to 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, and 0.75λ, the highest gain of 15.667 dBi is achieved at 0.75λ in the 2×4 array.

Parametric analysis shows that the effect of patch spacing on eco. From the graph analysis, by changing the horizontal and vertical distances in the patches of the 2×2 array to 0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ, it is seen that the maximum eco of 4.245 dB is observed at 0.55λ in the 2×2 array. From the graph analysis, by changing the horizontal and vertical distances in the patches of the 2×4 array to 0.5λ, 0.55λ, 0.6λ,

0.65λ, 0.7λ, 0.75λ, it is seen that the maximum eco of 7.187 dB is observed at 0.75λ in the 2×4 array.

From the analysis, it is seen that as the element increases, the gain also rise. The single-element gain is 6.585 dBi. The gain in a 2×2 array at horizontal and vertical distances (0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ) is (12.395 dBi, 12.61 dBi, 12.67 dBi, 12.478 dBi, 12.335 dBi, 12.315 dBi). The gain in a 2×4 array at horizontal and vertical distances (0.5λ, 0.55λ, 0.6λ, 0.65λ, 0.7λ, 0.75λ) is (14.743 dBi, 14.873 dBi, 15.349 dBi, 15.645 dBi, 15.352 dBi, 15.667 dBi). The gain increases from a 2×2 array to a 2×4 array. A compact microstrip 2×4 array antenna with series-corporate feed, both-sided MIC network will have gain values (15.667 dBi), eco (7.187 dB), reflection coefficient (-49.132 dB), simple impedance matching technique, reduced size, reduced side lobes, and reduced mutual coupling between elements. This antenna is capable of performing in the X-band frequency range. Applicable to radar, mobile, and medical.

5.3 Limitations of this Work

This 2×4 array antenna will be able to contribute heavily to wireless communication, but it has some limitations, which are as follows:

1. The polarization of this antenna is linear work at a frequency of 10 GHz and is unable to operate at multiple frequencies.
2. There is no system available to reconfigure this antenna.

5.4 Scope of future work

This thesis will contribute greatly to the antenna society. Modes of communication are increasing day by day. So, to keep ourselves updated, we need some changes in the communication systems. Reconfiguration of antennas can help us acquire better performances, which are as follows:

1. Antennas may have multiple polarizations.
2. Antennas can be able to operate at multiple frequencies.
3. Directivity will increase with increase in antenna elements.

REFERENCES

[1] Balanis, Constantine, “Antenna Theory-Analysis and Design”, John Wiley & Sons Ltd, Reprinted 1997.]

[2] S. R. Saunders and A. A. Zavala, Antennas and Propagation for wireless communication systems, Second edition. New York: Wiley, 2007.

[3] J. C. Maxwell, A Treatise on Electricity and Magnetism. London, U.K.: Oxford Univ. Press, 1873.

[4] J. Ramsay, “Highlights of antenna history,” IEEE Commun. Mag., vol. 19, no. 5, pp. 4–8, 1981.

[5] P. Israel, Edison: A life of invention, 1st. New York: John Wiley & Sons, 1998.

[6] G. Kizer, Digital microwave communication: engineering point-to-point microwave systems. John Wiley & Sons, 2013

[7] J. W. Klooster, Icons of invention: the makers of the modern world from Gutenberg to Gates. ABC-CLIO, 2009.

[8] C. A. Balanis, “Antenna technology: Past, present and future,” in IEEE Int. Workshop Antenna Technol. (iWAT), IEEE, USA, pp. 5–7, 2012.

[9] H. Yagi, “Beam transmission of ultra-short waves,” Proc. IRE, vol. 16, no. 6, pp. 715–740, 1928.

[10] R. L. Haupt, Antenna arrays: a computational approach. Hoboken, N.J: Wiley-IEEE Press, 2010.

[11] T. S. Rappaport et al., “Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!” IEEE Access, vol. 1, pp. 335–349, 2013.

[12] E. Levine, G. Malamud, S. Shtrikman, et D. Treves, “A study of microstrip array antennas with the feed network”, IEEE Trans. Antennas Propag., vol. 37, no 4, p. 426-434, avr. 1989.

[13] G. Wunder et al., “5GNOW: Non-orthogonal, asynchronous waveforms for future mobile applications,” IEEE Commun. Mag., vol. 52, no. 2, pp. 97–105, Feb. 2014.

[14] Z. Ying, “Antennas in cellular phones for mobile communications,” Proc. IEEE, vol. 100, no. 7, pp. 2286–2296, Jul. 2012.

[15] J. G. Andrews et al., “What Will 5G Be?” IEEE J. Sel. Areas Commun., vol. 32, no. 6, pp. 1065–1082, Jun. 2014.

[16] M. Shafi et al., “5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice,” IEEE J. Sel. Areas Commun., vol. 35, no. 6, pp. 1201–1221, Jun. 2017.

[17] V. Sharma, “Microstrip antenna-inception progress and current-state of the art review,” Recent Adv. Electra. Electron.Eng., vol. 13, no. 6, pp. 770–799, 2020.

[18] I. B. Sharma, B. Karla, and S. Srimal, “A design of multiband simple microstrip patch antenna by using inset-feed,” IEEE Indian Conf. Antennas Propag. (InCAP), pp. 194–197, 2021.

[19] R. Mishra, R. G. Mishra, R. Chaurasia, and A. K. Shrivastava, “Design and analysis of microstrip patch antenna for wireless communication,” Int. J. Innovative Tech. Exploring Eng., vol. 8, no. 7, pp. 663–666, 2019

[20] I. B. Sharma, B. Karla, and S. Srimal, “A Design of multiband simple microstrip patch antenna by using inset-feed,” IEEE Indian Conf. on Antennas and Propag. (InCAP), pp. 194-197, 2021

[21] R. G. Winch, Telecommunication Transmission System. The McGraw-Hill Companies, Inc., 1993.

[22] International Telecommunication Union. Radio-frequency channel arrangements for fixed service systems. Available: https://www.itu.int/dms_pubrec/itu-r/rec/f/R REC-F.746-5-200105-S!!MSW-E.doc.

[23] R. Bayderkhani and H. R. Hassani, “Wideband and low side lobe slot antenna fed by series-fed printed array,” IEEE Trans. Antennas Propag., vol. 58, no. 12, pp. 3898–3904, Dec. 2010.

[24] I. Slomian, I. Piekarz, and K. Wincza, “Microstrip antenna array with series feeding network designed with the use of slot-coupled three-way power divider.” IEEE Antennas Wireless Propag. Lett., vol. 11, pp. 667–670, 2012.

[25] K. Xing, B. Liu, Z. Guo, X. Wei, R. Zhao, and Y. Ma, “Backlobe and sidelobe suppression of a Q-band patch antenna array by using substrate integrated coaxial line feeding technique,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 3043–3046, 2017.

[26] E. Levine, G. Malamud, S. Shtrikman, and D. Treves, “A study of microstrip array antennas with the feed network,” IEEE Trans. Antennas Propag., vol. 37, no. 4, pp. 426–434, Apr. 1989.

[27] Y. Chong and D. Wenbin, “Microstrip series fed antenna array for millimeter wave automotive radar applications,” in Proc. IEEE MTI IMW, pp. 1–3, 2012.

[28] S. X. Ta and I. Park, “Compact wideband sequential-phase feed for sequentially rotated antenna arrays,” IEEE Antennas Wireless Propag. Lett., vol. 16, pp. 661–664, 2017.

[29] K. Wincza and S. Gruszczynski, “Microstrip antenna arrays fed by a series-parallel slot-coupled feeding network,” IEEE Antennas Wireless Propag.Lett., vol. 10, pp. 991–994, 201.

[30] Abdennaceur Baghdad, Abdelmajid Badri, Aicha Sahel," Design and Simulation of Microstrip Patch Array Antenna with High Directivity for 10 GHz Applications,” Conference: International Symposium on Signal Image Video and Communications, November 2014. July 2017.

[31] Tharian Joseph Pradeep, “Design of 4x2 Corporate Feed Microstrip Patch Antenna Using Inset Feeding Technique with Defective Ground Plane Structure,” Advances in Intelligent Systems and Computing, July 2017.

[32] Md. Tanvir Ishtaique-ul Huque, Md. Kamal Hosain, Md. Shihabul Islam, and Md. Al-Amin Chowdhury, “Design and Performance Analysis of Microstrip

Array Antennas with Optimum Parameters for X-band Applications,'' (IJACSA) International Journal of Advanced Computer Science and Applications, Vol. 2, No. 4, 2011.

[33] Benaouf Taleb Mohamed, Hassan Ammor, "A 16-elements Corporate-series Feed Rectangular Patch Antenna Array at 28GHz, for future 5G applications," International Conference on Wireless Information Technology and Systems,3 April 20191.

[34] Madhukant Patel, Piyush Kuchhal, Kanhiya Lal, Ranjan Mishra, "Design and Analysis of Microstrip Patch Antenna Array using Different Substrates for X-Band Applications," International Journal of Applied Engineering Research ISSN 0973-4562, Volume 12, Number 19 (2017) pp. 8577-8581.

[35] Noor Syazwani Razak, Shaharil Mohd Shah, "Antenna for 5G Mobile Communication at 28 GHz," Journal of Electronic Voltage and Application, vol. 3, no. 1 (2022) 33-44.

[36] A D Santoso, F B Cahyono, I Suwondo, Arleiny, B B Harianto, "Microstrip Antenna Design with Array Rectangular Patch 2×2 for Ship Radar at 2.2 GHz," Journal of Physics: Conference Series, 2117 (2021) 012019.

[37] Mr. V. Ganesh, S. Rajkumar, F.S. Umarfarook, S.N. Sridhar, "Design of Patch Antenna and Array for Wireless Communication," International Research Journal of Modernization in Engineering Technology and Science, Volume:04, Issue:01, January 2022.

[38] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, "Microstrip Antenna Design Handbook," Artech House (2000).

[39] 38 K. Gi-Cho, et al., "Ku-band high efficiency antenna with corporate series-fed microstrip array," in Antennas and Propagation Society International Symposium, IEEE, 2003, pp. 690-693 vol.4,2003.

[40] Devi Perla, Rajya Lakshmi Valluri, Harish Chunduri, T.D.V. Gayathr, "A Comparison Analysis of 2X1 Series Feed Array Antenna for Satellite Applications," International Journal of Innovative Technology and Exploring Engineering (IJITEE), ISSN: 2278-3075, Volume-8, Issue-6S3, April 2019.

[41] Leela Rani, P. Siddaiah, "1×4 Rectangular Patch Array Operating at 10GHz Using Corporate Feeding Technique 1K," © 2017 IJEDR, Volume 5, Issue 2, ISSN: 2321-9939.

[42] F. T. Ulaby, E. Michielssen, and U. Ravaioli, "Fundamentals of applied electromagnetics 6e," Boston, Massachusetts: Prentice Hall, 2010

[43] C. A. Balanis, Antenna theory: analysis and design. John Wiley & Sons, 2016

[44] Balanis C. A. Antenna Theory: Analysis and Design (3rd edition), 2005

[45] H. W. Silver, Ed. The ARRL Antenna Book for Radio Communication, 22nd.The National Association for Amateur Radio, Newington, 2011.

[46] Balanis, Constantine, "Antenna Theory-Analysis and Design", John Wiley & Sons Ltd, Reprinted 1997.

[47] Wai-Kai Chen, The Electrical Engineering Handbook, Academic Press, 2003

[48] N. Ullah, Z. Huiling, T. Rahim, S. ur Rahman, and M. Muhammad Kamal, "Reduced side lobe level of sparse linear antenna array by optimized spacing and excitation amplitude using particle swarm optimization," in 2017 7th IEEE International Symposium on Microwave, Antenna, Propagation, and EMC Technologies (MAPE), 2017, pp. 96-99: IEEE.

[49] A. Z. Elsherbeni, C. Reddy, and P. Nayeri, Antenna analysis and design using Feko electromagnetic simulation software (Aces series on computational electromagnetics and engineering). SciTech Publishing, 2014.