Multi-Beam Near Field Focusing Characteristics of Microstrip Patch Antenna Array

Muhammad Sohail

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Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy in Electrical and Electronic Engineering.

Assoc. Prof. Dr. Rasime Uyguroğlu
Chair, Department of Electrical and Electronic Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Doctor of Philosophy in Electrical and Electronic Engineering.

Prof. Dr. Abdullah Y. Öztoprak
Co-Supervisor

Assoc. Prof. Dr. Rasime Uyguroğlu
Supervisor

Examining Committee

1. Prof. Dr. Hasan Demirel
2. Prof. Dr. Mehmet Kuşaf
3. Prof. Dr. Özlem Özgün
4. Prof. Dr. Abdullah Y. Öztoprak
5. Prof. Dr. Birsen Saka
6. Prof. Dr. Şener Uysal
7. Assoc. Prof. Dr. Rasime Uyguroğlu

ABSTRACT

Several modern-day antenna applications require the radiated fields to be focused at a predetermined point away from the antenna to perform different tasks, such as sensing, testing, charging, diagnosing, and treatment of different medical conditions. In this thesis, a thorough study has been made to investigate the characteristics of near-field focusing. In many applications, along with focusing the radiated fields at a focal point, it is also required to move that focused beam to scan a specific region i.e., usually carried out either electronically or physically by changing the position of the antenna array. The thesis proposes a robust mechanism to move the focused beam at single and dual focal points to improve the scanning properties of the antenna array. The proposed mechanism does not depend upon any external phase shifter circuit or changing the position of the array for focusing and scanning the focused beam. The movement of the focused beam is achieved as a result of introducing extra transmission lines to the scanning axis of the array.

Antenna designs for single-focal and dual-focal points are analyzed using MATLAB and CST simulation software. The simulation results show that the proposed designs work efficiently as the movement of the beam is controlled by the change in frequency. Furthermore, in the case of dual focal point near field focused antenna array, there is a significant increase in the scanning distance as compared to the single focal point. The proposed mechanism results in an increment in scanning distance of around 53%. The proposed designs can be used in applications such as RFID, Non-destructive industrial inspection and testing, and wireless power transfer, where the focused beam is to be directed at a point in the near-field and the scanning of the focused beam is required as well.

Keywords: microstrip patch antenna array, near-field focusing, parasitic patch, hyperthermia, beam scanning.

ÖZ

Günümüzün bazı anten uygulaması, farklı tıbbi durumların algılanması, test edilmesi, şarj edilmesi, teşhis edilmesi ve tedavisi gibi farklı görevleri gerçekleştirmek için yayılan alanların antenden uzakta önceden belirlenmiş bir noktaya odaklanmasını gerektirir. Bu tezde, yakın alan odaklamanın özelliklerini araştırmak için kapsamlı bir çalışma yapılmıştır. Pek çok uygulamada, yayılan elektromagnetik alanları bir odak noktasına odaklamanın yanı sıra, odaklanan ışını belirli bir bölgeyi taramak için anten dizisinin konumu elektronik veya fiziksel olarak hareket ettirerek değiştirmek de gerekir. Tez, anten dizisinin tarama özelliklerini iyileştirmek için odaklanmış ışını tek ve çift odak noktalarında hareket ettirmek için bir yöntem önermektedir. Bu şalışma, anten dizisinin tarama özelliklerini iyileştirmek için odaklanmış ışını tek ve çift odak noktalarında hareket ettirmek için bir mekanizma önermektedir.

Önerilen mekanizma ile, ışını odaklamak ve taramak yapmak için herhangi bir harici faz kaydırma devresine veya dizinin konumunu değiştirmeye gerek duyulmamamktadır. Tek odak noktası ve çift odak noktası için anten tasarımları MATLAB ve CST simülasyon yazılımı kullanılarak analiz edilir. Benzetim sonuçları, hüzme hareketi frekanstaki değişiklik tarafından kontrol edildiğinden önerilen tasarımların verimli çalıştığını göstermektedir. Ayrıca çift odak noktalı yakın electromagnetik alan odaklı anten dizisi durumunda, tek odak noktasına göre tarama mesafesinde önemli bir artış vardır. Önerilen tasarımlar, odaklı ışının belirli bir noktaya yönlendirilmesi ve aynı zamanda bu odaklı ışının taranması gereken uygulamalarda kullanılmak üzere tasarlanmaktadır. Bu uygulamalar arasında RFID, yıkıcı olmayan endüstriyel muayene ve test, kablosuz enerji transferi gibi alanlar bulunmaktadır.

Anahtar Kelimeler: mikroşerit yama anten dizisi, yakın alan odaklama, parazitik yama, ışın tarama

.

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LIST OF SYMBOLS

γ	Coefficient of Focal Shifting
λ_0	Free Space Wavelength
f	Frequency
Φ	Phase
ε_r	Relative Permittivity
w	Transmission Line Length
λ_g	Wavelength in Dielectric
k	Wave Number

LIST OF ABBREVIATIONS

EBG	Electromagnetic Band Gap
NFF	Near-Field Focusing
NFC	Near Field Communication
RFID	Radio Frequency Identification
VNA	Vector Network Analyzer

Chapter 1

INTRODUCTION

1.1 Introduction

Antennas are one of the integral parts of modern-day technologies and devices, not only for telecommunications but also for performing different essential tasks. Planar printed antennas such as microstrip patch antennas are versatile antennas due to their advantages such as being less bulky, less costly, conformability, and most importantly their compatibility with integrated circuits i.e. Monolithic Integrated Circuit Technology (MMIC). These antennas have been used extensively over the past decades due to their simple geometrical structure which makes them easy to fit in most scenarios.

Microstrip patch antennas can be found nowadays in applications ranging from communications, radars, sonars, military, and industries to satellite and biomedical sectors [1-3]. Depending upon the requirements of the application area, these antennas can be used in far-field (for large distances) or near-field (for close distances). For instance, radar uses patch antennas for detecting and communicating with different identified and unidentified targets at large distances, hence they rely on the far-field radiated fields of the antennas while an emerging technology named Near-field Communication (NFC) relies on the near-field radiated fields of the antennas to perform the transmission of data. Both the near-field and far-field radiated fields of the antennas have their own advantageous and limitations and hence they exploit these characteristics to be used in specific applications.

A phased array antenna is a type of antenna array that controls the radiation pattern of the antennas by variation in phase of individual array elements [4]. Focusing, scanning, and shaping the radiation pattern are a few of the many phased array applications. Near-field focusing, is an application of the phased arrays, where the radiated fields from the antenna array are focused at a specified point called the focal point in the closed vicinity of the array i.e. near-field. Over the last few decades, near-field focusing has been used in various fields such as Radio Frequency Identification (RFID) [5-6], Industrial sensing and testing [7], gate control [8], biomedical [9-10], and wireless charging applications [11-12].

1.2 Thesis Objective

The objective of the thesis can be categorized into two parts, near-field focusing and moving the near-field focused beam as a function of frequency. In near-field focusing applications, the goal is usually to converge the radiated fields from the antenna array aperture at a predetermined point to increase the intensity of the fields. As a result of focusing a small focused spot is achieved as compared to an unfocused or far-field focused antenna array. That focused spot is then used to perform different tasks ranging from reading, sensing, inspection, testing, and treatment. To focus the radiated fields from an antenna aperture, the individual elements of the array must be in phase at the focal point. To do so, the transmission line that is fed to each element of the array is designed in such a way that irrespective of how far or close the element is to the focal point, all the elements will end up being in phase at the focal point. Being in phase at the focal point results in constructive interference and the magnitudes are added forming a highly concentrated beam.

Near-field focused beam scanning is of great importance in several applications, where the focused beam has to be shifted or moved in a certain direction. Beam scanning is usually done either electronically or by physical means. Electronic beam scanning involves phase-shifting circuitry, while by physical means either the antenna array or the target needs to be moved/shifted. In this thesis, to achieve the objective of scanning the near-field focused beam, neither conventional phase-shifting circuitry nor any physical means is used. The scanning has been achieved by using multiple wavelengths long extra transmission lines, at the design frequency. As the frequency changes, these extra transmission lines are no longer wavelength long. As a result, a progressive phase is introduced at each antenna element and the focused beam is shifted in a certain direction depending on the phase difference.

The scanning of the near-field focused beam plays a vital role in applications, where not only a highly concentrated beam is required but the scanning of the said beam is the aim. For instance, in non-destructive industrial inspection and testing, a highly concentrated beam is to be directed to the product in the test, to acquire different properties. The focused beam is to be scanned so that the whole region of interest is covered. The whole process is carried out without breaking or damaging the material or product under the test. Some of the other applications include RFID and wireless power transfer.

The main accomplishment of the thesis is to scan the near-field focused beam as a function of frequency, where the mechanism is robust, and does not depend on any external circuitry or changing the position of the antenna array. The antenna array does not require a separate phase distribution each time, the change in frequency translates into a respective change in the position of the focused beam.

1.3 Thesis Contribution

In this thesis, a meaningful contribution has been made to the applications of microstrip patch antenna arrays in the near-field. Microstrip patch antennas are low-profile antennas with very limited power handling capabilities. In applications such as Radio Frequency Identification (RFID), it is possible to have multiple reading tags (targets) close enough together to have a low probability of detecting a false tag [13]. Having more power in the region of interest increases the probability of detecting the right tag. Parasitic patches along with a conventional near-field focusing antenna array enhance further the concentration of the focused fields without extracting extra power from the source. This contributes to both the improvement of detection probability and reducing the power consumption.

Scanning or moving the focused radiated fields is of great importance in applications where the region of interest is large or there are multiple targets to be tackled. In these cases, the position of the focused spot should be moved. Conventionally, it is done either using phased array antennas or an external mechanism such as human interaction or any mechanical involvement is used to move the antenna array. Both the methods are not efficient as well as robust and there is a high probability of error. The proposed antenna array system in this thesis contributes to those applications and the movement of the focused spot is achieved by varying the frequency of the system, without any physical changes to the existing system. It increases the efficiency of the system as well as reduces the risk of errors.

1.4 Thesis Organization

The thesis is comprised of seven chapters, Chapter 1 gives a brief introduction to the thesis, the contribution, and motivation of the thesis. Chapter 2 provides the details about the basics of patch antennas and patch antenna arrays. It explains the advantages, disadvantages, and the application areas where patch antennas are used. Near-field focusing is the main subject in chapter 3. This chapter gives an insight into the basic workings of near-field focusing along with the key areas of concern in the near-field focusing. Chapter 4 consists of a proposed patch antenna array design using parasitic patch elements to enhance the concentration of the already focused radiated fields. Chapter 5 discusses the concept of moving the focused radiated spot as a function of frequency for applications, where a large region or multiple points along a line is to be targeted. The proposed system is discussed in detail to understand the working mechanism of focused spot moving with frequency variation. Chapter 6 explains dual focal point near-field focused antenna arrays. The main goal of this chapter is to increase the scanning distance of the near-field focused antenna arrays. Chapter 7 concludes the thesis and provides a brief study of the future work. The future work includes the validation of the proposed designs by carrying out the necessary fabrication and measurement processes.

Chapter 2

MICROSTRIP PATCH ANTENNA ARRAY

2.1 Microstrip Patch Antenna

Microstrip radiators were first patented in 1955 with the names Gutton and Baissinot in France [14] but the concept of microstrip radiators was first proposed by Descamps [15] in 1953. In the next 20 years, microstrip radiators saw a slow growth of development until in 1970s. The availability of better substrates with low-loss tangents and the development of photolithography techniques made it possible for microstrip radiators to accelerate the pace of development. In that era, numerous theoretical models of microstrip antennas were developed, which led to the manufacture of the first practical microstrip antennas by Howell [16] and Robert E. Munson [17]. Since then microstrip patch antennas have seen a rapid development in industrial as well as the research perspective. The pace of development would not have been possible due to the versatility of the microstrip patch antenna i.e. their conformal nature, low weight, less costly, and most importantly its compatibility with the Monolithic Microwave Integrated Circuits (MMIC). The antenna can be fed using different feeding techniques [18] such as coaxial feed, microstrip feed, aperture feed, and proximity feed. All the feeding techniques have their advantages and disadvantages and are highly dependent upon the application for which the antenna is being designed. A basic microstrip patch antenna consists of three major parts. A conducting patch, a dielectric substrate, and a ground plane. The dielectric substrate with relative permittivity ε_r is sandwiched between a conducting patch and the ground plane as shown in Figure 1. The patch is also called a radiating patch. Usually, the patch and ground planes are made up of gold or copper due to their high conductivity but since gold is expensive, mostly copper is used.

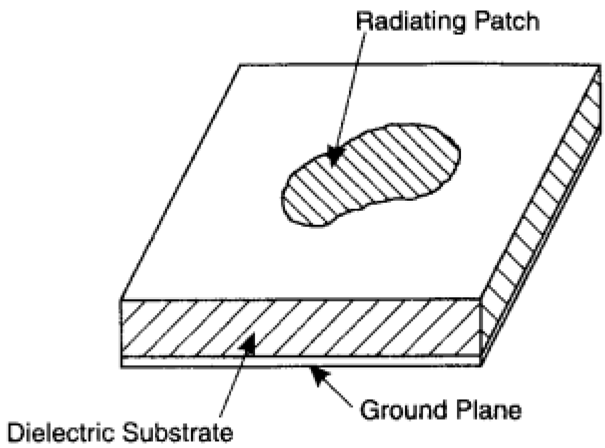

Figure 1: Microstrip Patch Antenna [19]

Compared to conventional microwave antennas, microstrip patch antennas have several advantages and disadvantages. A microstrip patch antenna is light weight and takes less volume. It is a low-profile antenna and can be used in a conformal configuration. Its manufacturing cost is low, hence can be mass produced. It is compatible with Monolithic Microwave Integrated Circuits, which enables it to be used in a variety of applications. It supports linear and circular polarization with the same excitation. One of the major disadvantages of a patch antenna is that it has a narrow bandwidth. A patch antenna is a low gain antenna, typically in the range of approximately 6 dB. In the case of a patch antenna array the feeding network is fabricated simultaneously and is a part of an antenna array, there are considerably large conductor or ohmic losses in the array feed network. It is very difficult to achieve pure polarization. As the microstrip patch antenna is a low-profile antenna, hence its power handling capability is very low. The limitations mentioned above are not impossible to remove or reduce. In the literature, several techniques and methods are implemented to reduce or get rid of the above-mentioned limitations.

Although the patch can be of any geometrical shape mostly the regular geometrical shapes are considered as their theoretical and mathematical models are available in the literature. Rectangular, square, and triangular shapes of patches are the ones widely used. A few of the basic patch shapes are given in Figure 2.

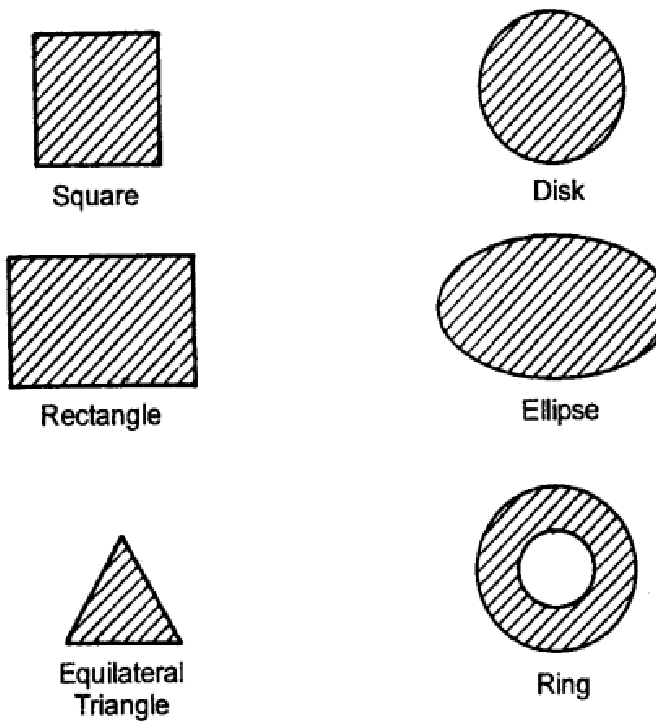

Figure 2: Basic Patch Shapes [19]

2.2 Feeding Techniques

Feeding a patch antenna means exciting it with a microwave source. Microstrip patch antenna uses different configurations of feeding but they are divided into two categories namely contacting and non-contacting feeding techniques. As the name suggests, the contacting feeding techniques are those in which the excitation source or transmission line is directly connected to the radiating patch such as coaxial feed and microstrip feeding techniques. Contacting feeding techniques, and non-contacting feeding techniques are used for electromagnetic coupling of power to the patch. Aperture and proximity coupling are examples of non-contacting feeding methods.

2.2.1 Coaxial Feed

The basic component of the coaxial feeding is coaxial cable. A basic coaxial cable consists of two conductors and a dielectric to insulate the conductors from each other. A coaxial cable is cylindrical with an inner solid conductor and an outer stranded conductor. Both the conductors are isolated from each other using a dielectric in between. The dielectric usually used in coaxial cable is Teflon with relative permittivity of 2.1. The diameters of both conductors and dielectric decides the impedance of a coaxial cable.

A rectangular patch antenna can be observed in Figure 3, fed using a coaxial cable. The inner conductor of the coaxial cable is connected directly to the patch while the outer stranded conductor is connected to the ground plane.

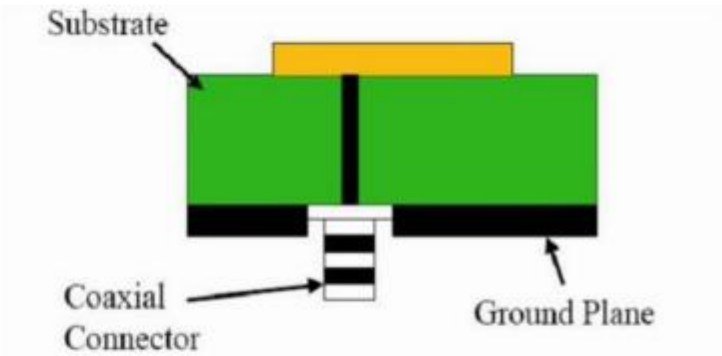

Figure 3: Coaxial Fed Microstrip Patch Antenna [20]

The edge impedance of patch antennas is usually high as compared to the coaxial cable, 50 Ω normally, so it is very important for both the impedances to be matched and to make sure maximum power transfers between the antenna and transmission line. To achieve the maximum power transfer, it is important to determine the feed position corresponding to the matched impedance.

2.2.2 Microstrip Line Feed

A type of contacting feeding method in which a microstrip line is etched and connected directly to the patch. The microstrip line is easy to fabricate and withstand more stress as compared to coaxial feed, where the transmission line conductors are soldered to the antenna. The microstrip is a narrow strip of the same conductor as the patch. The impedance of the microstrip line depends upon the width of the feedline as well as the thickness and relative permittivity of the dielectric substrate used for the antenna. Figure 4 shows a microstrip patch antenna excited using a microstrip line.

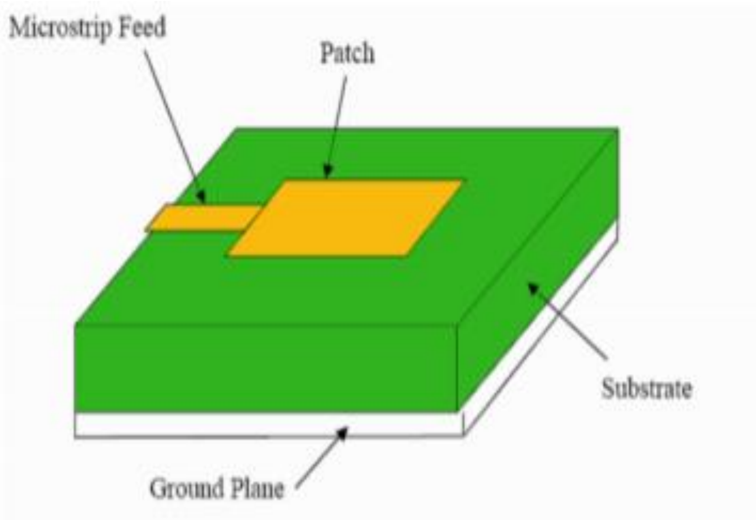

Figure 4: Microstrip Fed Patch Antenna [20]

2.2.3 Aperture Coupling Feed

Aperture coupling is a non-contacting feeding technique, where the feedline is electromagnetically coupled to the radiating patch using a coupling slot in the ground plane. Aperture coupling consists of two substrates namely the antenna substrate and the feed substrate. The radiating patch is kept on the antenna substrate and below the antenna substrate, the ground plane lies. A microstrip feed line lies at the bottom of the feed substrate, which lies just below the ground plane. The length and width of the coupling slot are used to match the feedline and antenna impedance from maximum power transfer.

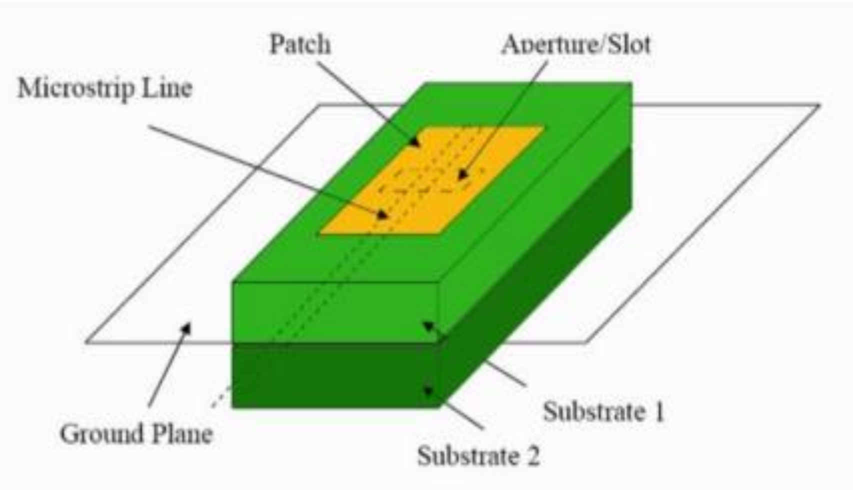

Figure 5: Aperture Coupled Microstrip Patch Antenna [20]

2.2.4 Proximity Coupling Feed

Proximity coupling is also a type of non-contacting feeding technique that also uses two substrates. A radiating patch is etched above the antenna substrate. Below the antenna substrate lies the feed substrate on top of which a microstrip feed line is etched. The lowermost layer is the ground plane.

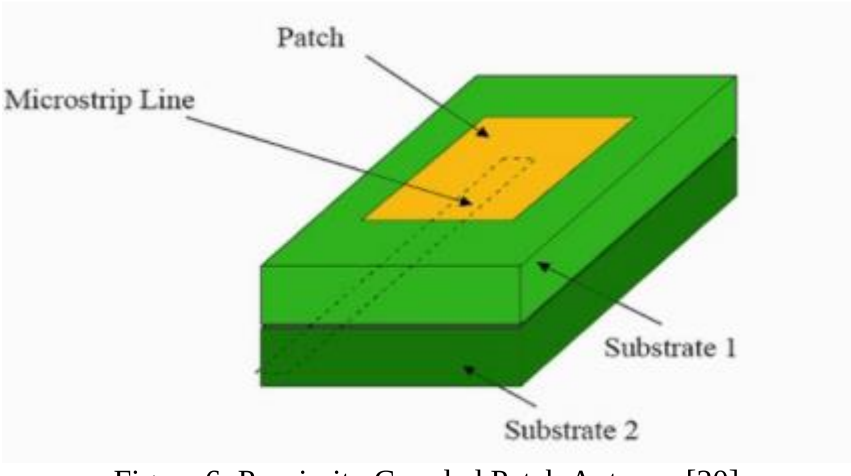

Figure 6: Proximity Coupled Patch Antenna [20]

This type of feeding technique depends upon electromagnetic coupling where the feedline does not have any direct connection with the patch. A proximity-coupled microstrip patch antenna is shown in Figure 6. Several other feeding techniques can be considered as modified versions of the above-discussed techniques. All the above-mentioned feeding technique have their advantages and disadvantages. The selection criteria of the feeding technique mostly depend upon the application area as well as available tools and facilities.

2.3 Microstrip Patch Antenna Array

The selection of antennas is highly dependent upon the application area. The requirements of certain applications may be fulfilled by a single antenna but some applications rely on the combined operation of multiple antennas. Usually, microstrip patch antennas are classified as low to moderate gain antenna and a single microstrip patch antenna might not be enough for applications where the requirement is a high gain, directivity, and steering or scanning of the beam. In such scenarios, it is intended to arrange multiple antennas in a specific configuration called an antenna array. Each antenna in the array is called an element of the array. Usually, the elements in the array are identical and the total array pattern can be found using the pattern multiplication theorem [21].

$$\text{Array Pattern} = \text{Element Pattern} \times \text{Array Factor} \tag{2.1}$$

Elements pattern refers to the radiation pattern of a single element in the array, as the array elements are identical, so the element pattern would be the same for all elements, while the array factor is a function based on the array geometry as well as the excitation source. The amplitude and phase of the excitation source are considered while calculating the array factor.

One of the main advantages of microstrip patch antenna over the wire or other types of antennas is the easiness of integrating and combining them in the form of an array. Based on the arrangements of patch antenna elements in the array, the antenna arrays can be categorized into different types;

- Linear Microstrip Patch Antenna Array
- Planar Microstrip Patch Antenna Array.

2.4 Linear Microstrip Patch Antenna Array

When the elements of the array are arranged along a straight line, it becomes a linear array. It can be either a uniformly spaced array, where the inter-element distance between the elements is uniform, or an unequally spaced linear antenna array, where the inter-element distance is kept non-uniform. A linear array can be fed using different arrangements of feed networks such as Series or parallel feed. A brief discussion about feed networks is elaborated in the next sections. A linear arrangement of 8 elements rectangular patch antenna array is shown in Figure 7 [22].

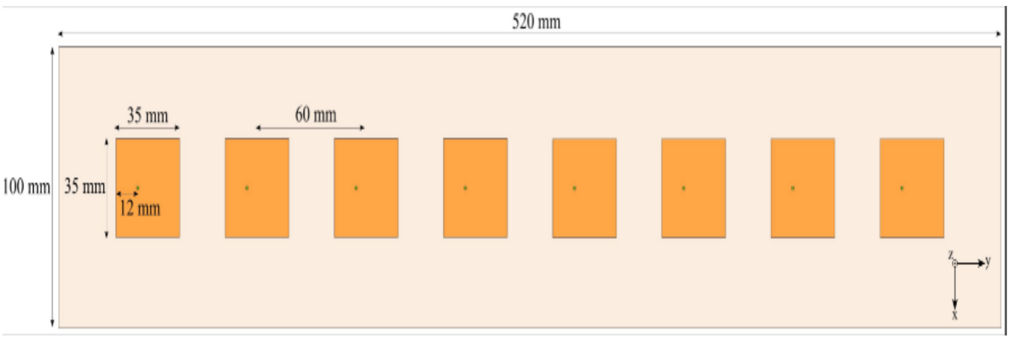

Figure 7: Linear Microstrip Patch Antenna Array [22]

2.4.1 Series Fed Linear Microstrip Patch Antenna Array

In series fed microstrip patch antenna array, the elements of the array are connected to the transmission line in series. An 8-element series-fed microstrip patch antenna is shown in Figure 8, where the elements are connected using a microstrip transmission line in a series arrangement. The first element of the array is fed directly from the source while the other elements are fed using the continuity of the main feed line.

Figure 8: Series Fed Linear Microstrip Patch Antenna Array [23]

As the array is fed with a single series line and the feed network is compact, there are low line losses as compared to parallel feed networks. One of the main disadvantages of the series-fed linear arrays is that each element in the array has a direct impact on other elements, since the power to each element is transferred from the previous element, any discontinuity or error during the fabrication process will degrade the performance of the whole array. Although series-fed linear antenna arrays suffer from the drawback of narrow bandwidth there are several techniques used by the researchers to sort out the bandwidth issue.

2.4.2 Parallel Fed Linear Microstrip Patch Antenna Array

The parallel feeding technique is also called a corporate feed. This is one of the mostly used techniques, where the microstrip transmission line is fed parallel to each element of the array. Each element in the array is fed independently from other feed networks as well as the other elements in the array. An 8-element linear microstrip patch antenna array can be observed in Figure 9, where a single excitation source is divided into 8 independent feed lines and fed to each element of the antenna array. The power dividers are usually based on Wilkinson Power dividers. The parallel or corporate feed networks do have a broader bandwidth as compared to the series one but it comes with the expense of feed network complexity.

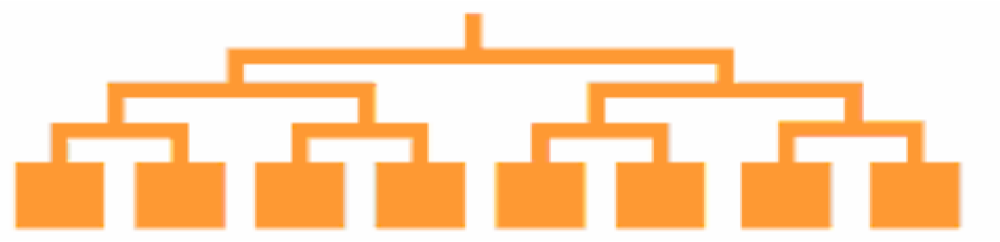

Figure 9: Parallel Fed Microstrip Patch Antenna Array [23]

2.5 Planar Microstrip Patch Antenna Array

In planar microstrip patch antenna array systems, the antenna elements are positioned along a plane rather than in a line. The antenna elements for a grid of certain shape are usually rectangular, square, or circular shape but not necessarily as recently researchers have become more interested in positioning the elements along a plane in a non-uniform way called as sparse antenna array. Planar antenna arrays have narrower beams as compared to linear arrays and are mostly used in applications where a narrow or pencil beam is required such as radar and communication applications. Multiple linear antenna arrays can be combined to form a planar antenna array.

A planar 8×8 (64 elements) microstrip patch antenna array can be seen in Figure 10. Assume that the elements are kept along the x-y plane. The inter-element distance along the x-axis and y-axis is kept uniform although it can be kept non-uniform as well.

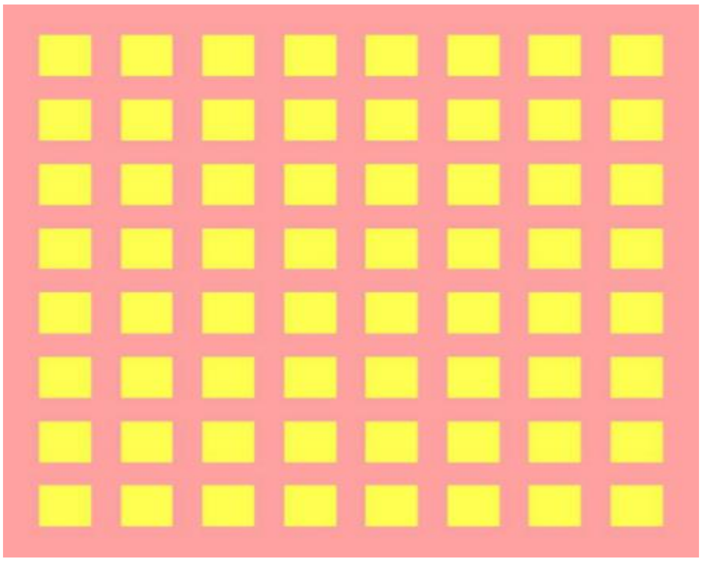

Figure 10: Planar Microstrip Patch Antenna Array

2.5.1 Series Fed Planar Microstrip Patch Antenna Array

Multiple series-fed linear patch antenna arrays can be arranged in a specific configuration to form a series-fed planar microstrip patch antenna array. A 32 elements planar patch antenna has been formed by combining 8 sections of 4 elements linear patch antenna arrays shown in Figure 11. Although all the sections are combined using a parallel feed since the elements of each section are connected in series, it can be called a series patch antenna array. Like any other planar antenna array, the elements can be kept either equally or unequally spaced.

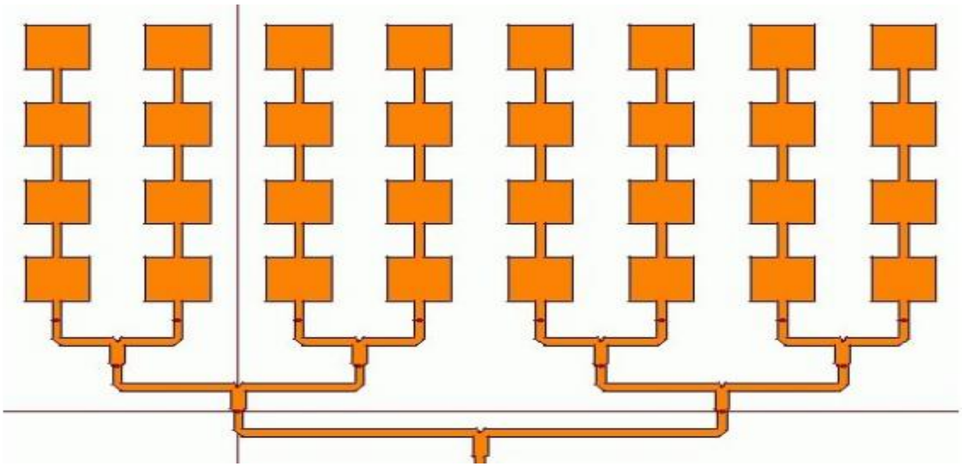

Figure 11: Series Fed Planar Patch Antenna Array [24]

2.5.2 Parallel or Corporate Fed Planar Microstrip Patch Antenna Array

A corporate-fed planar microstrip patch antenna array uses a complex feed network where the feedline is divided into several independent feed lines that are fed to each element of the array separately. As mentioned earlier, corporate feed networks use power dividers/combiners based on Wilkinson power dividers. A 32 elements corporate-fed rectangular patch antenna array can be observed in Figure 12, where a single input source is divided into 32 equally divided feed lines and is fed to each element in the array. These feed networks are more complex as compared to linear arrays as the feed line goes through the spaces between antenna elements and can result in mutual coupling.

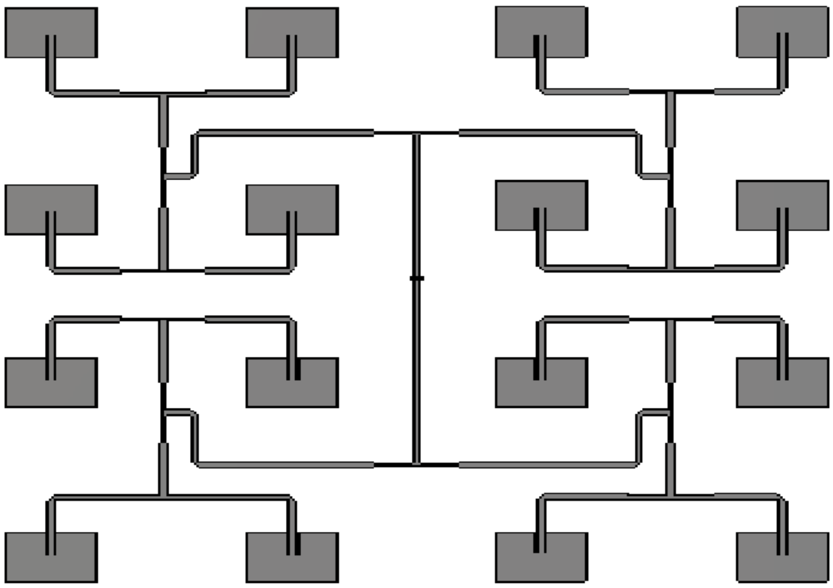

Figure 12: Corporate Fed Microstrip Patch Antenna Array

As discussed previously all the above-mentioned topologies of microstrip patch antenna array, the overall radiation pattern of the antenna array not only depends upon the arrangement of the elements but also the excitation source. The excitation source has two main parts, the magnitude and the phase of the excitation source. Based on the possible combinations of magnitude and phases, the elements in the array can have;

- Same magnitude, same phases
- Different magnitude, same phases
- Different magnitude, different phases
- Same magnitude, different phases.

The difference in the magnitude and phases are usually used to shape the radiation pattern of the array. A type of antenna array, where the elements of the array are fed with different phases irrespective of the magnitude to achieve a specific radiation pattern is called a Phased array.

2.6 Phased Microstrip Patch Antenna Array

Most communication systems, radars, industrial, and biomedical applications use phased antenna arrays, as all these applications are highly dependent upon the overall pattern of the antenna array. A phased antenna array uses a certain set of phases relative to the source to be fed to each element of the array to scan, steer, or shape the resulting pattern and get rid of radiation patterns in the unwanted direction [26]. For instance, in radar and sonar systems, where the primary goal is to scan a specific area, it is possible to replace the moving antennas with a phased antenna array and the scanning would be done electronically instead of moving the whole system.

The phased antenna arrays somehow behave as spatial filters as they only allow the radiation in a specific direction while blocking it in unwanted directions. Consider a linear phased array of K elements with inter-element distance d in between, fed by a corporate feed network as shown in Figure 13. The magnitude a_i as well as the phase Φ_i of the divided signal which is fed to each element can be controlled. By varying the phase of each element, the radiated fields from each element can be controlled and directed to an angle θ, which is the angle between the radiated field and the antenna array aperture normal.

This unique property of phased array to direct the radiated fields in a certain required direction and block them in unwanted directions opened up several opportunities for applications that require beam forming, scanning, and focusing. Since the scope of our thesis is mainly focusing on the radiated fields at certain points or in certain directions, the properties of the phased arrays will be used in the next chapter.

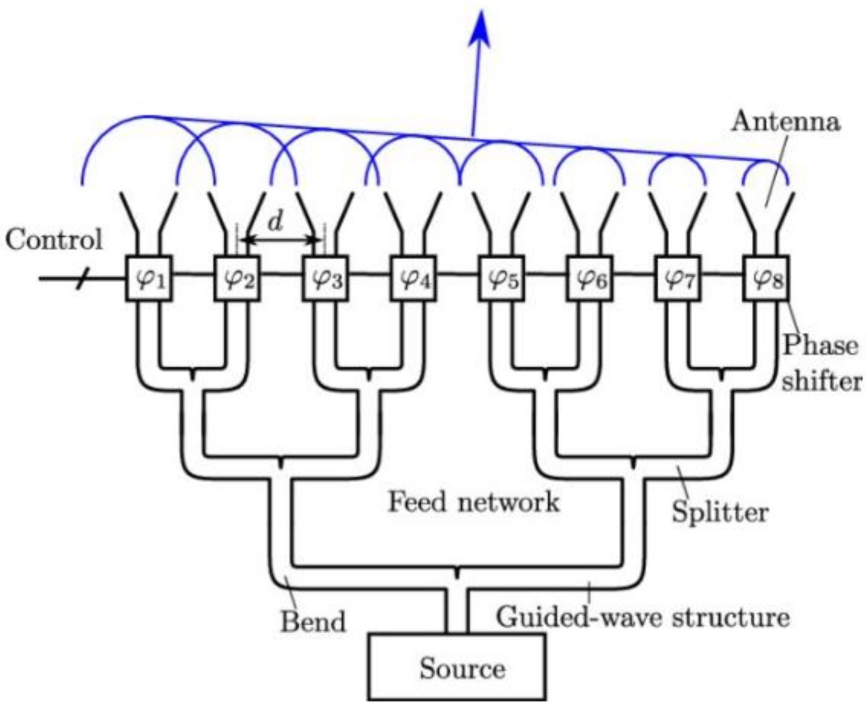

Figure 13: Linear phased antenna array [27]

Chapter 3

NEAR-FIELD FOCUSING OF MICROSTRIP PATCH ANTENNA ARRAY

3.1 Introduction

The region around the antenna or antenna array has been divided into different categories based on how close it is to the aperture. When the radiated fields are discussed, it is very important to know the relative distance from the antenna, where the fields are analyzed. The space surrounded by an antenna is broadly divided into two regions namely, near-field and far-field. The near-field region is further divided into reactive near-field and radiative near-field. The region just right next to the antenna is known as the near-field region. The outer boundary of the near-field region lies approximately at a distance of R_1 from the antenna aperture as shown in Figure 14, where R_1 is given as;

$$R_1 < \frac{2D^2}{\lambda} \tag{3.1}$$

Where D is the largest dimension of the antenna aperture and λ is the wavelength of the electromagnetic wave.

Far-field regions happen to be at distances larger than R_1. Most of the antenna measurements are done at the far-field because, in the far-field the radiated power decays at the rate of inverse square law to the distance from the antenna, while in the near-field the power level decays at a much higher rate. Also, it is much easier to measure the radiated fields at the far-field, as the radiation pattern is more uniform as compared to the near-field. That is why most antenna applications prefer far-field measure the radiated fields at the far-field, as the radiation pattern is more uniform as compared to the near-field. That is why most antenna applications prefer far-field operations as compared to the near-field but recently researchers have been interested in working in the near-field due to the reason that certain applications operate in the region very close to the antenna. Some applications will use near-field for their operations, as higher intensities of radiated power, as well as limited coverage area, are required. As the distance from the antenna aperture increases, the power level decreases as well as the coverage area of the radiated wave increases. For instance, Near-field Communication (NFC) [3] is one of the recent technologies, which uses near-field for their operation. For the transfer of information to take place between the transmitter and receiver of the NFC devices, both devices must be in close contact with each other. Other than NFC, several applications in the literature can be found using the near-fields as their region of operation. The applications include Radio Frequency Identification (RFID) [5-6], Wireless power transfer [11-12], Industrial Testing and Sensing [7], and biomedical applications [9-10], such as imaging, diagnosing, and treatment of various medical conditions.

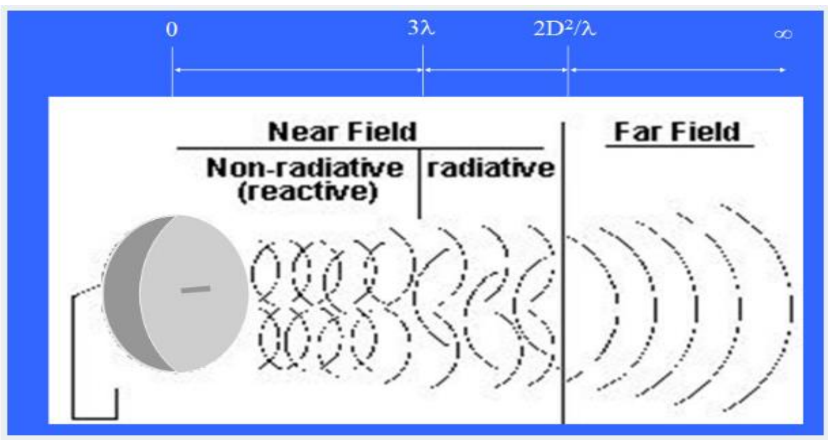

Figure 14: Regions around an Antenna [28]

Near-field focusing is one of the near-field applications where the radiated field from the aperture of the antenna is collected and converged at a specified point or region in the near-field. Because the microstrip patch antenna is compatible with MMIC technology, the conventional near-field focusing antenna such as a lens and reflectors antenna were soon replaced by the microstrip patch antennas. It is also a fact that technologies and devices are getting compact and reduced in size, the antennas need to be compatible with those technologies as well. Nowadays planar antennas are used for near-field focusing because of their compatibility with the latest technologies and devices, unlike the conventionally used antenna such as placing a dielectric lens in front of horn antennas and reflector antennas, which makes the system very bulky and heavy. The focusing of the radiated fields is usually achieved by using a planar antenna array specifically microstrip patch antenna arrays. A constructive interference is achieved at the designated focal point by controlling the phase of each element of the array.

The basics of optical lenses help in understanding the operations of focusing the radiated fields from the antenna aperture at a certain point. Concave and convex lenses are two of the basic lenses that diverge and converge the light waves at a certain region or point called a focal point. Assume a setup in which the optical wave fronts are to be passed through a convex lens. All optical lenses have their focal lengths, which is the distance along the optical axis of the lens to the focal point of the lens. The waves striking the aperture of the lens at different points converged at a pre-specified focal point. The curved surface of the lens as well as the refractive indices drives the whole focusing and defocusing phenomena.

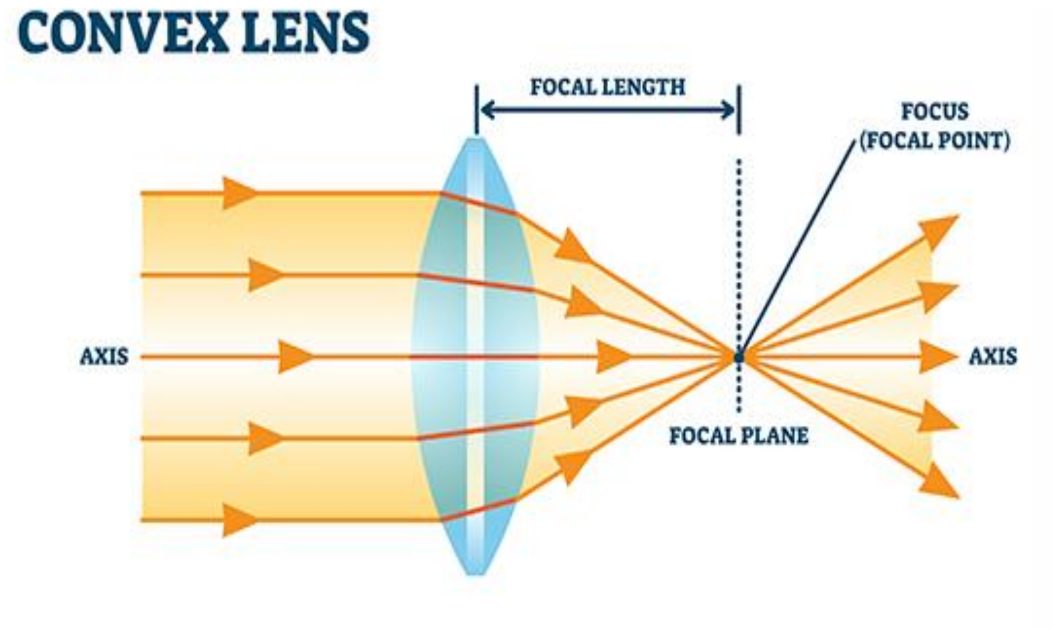

Figure 15: Convex Lens

The same analogy can be applied to the antennas for focusing the radiated fields at a certain point. The origin of focusing the radiated fields from the antenna comes from the use of dielectric lenses. Lodge and Howard [29] used a dielectric in their experiment in 1888 at the wavelength of 1 meter but the real progress in dielectric lenses for the use of focusing was made after the Second World War. At that time lenses were used basically to transform the radiation pattern of the antenna into a high-gain radiation pattern. These high-gain radiation patterns were then to be used for applications requiring fixed beam or beam scanning. Later on, the dielectric lenses were replaced by reflectors [30], where the non-converged radiation pattern from the source antenna converges to a focal point after striking the surface of the reflectors. Reflectors in that era were not as bulky as the lenses, so soon lenses were superseded by the reflectors. Figures 16 (a) and 16 (b) depict the basic principle of focusing the radiated fields at the focal point in the case of dielectric lenses and reflectors respectively.

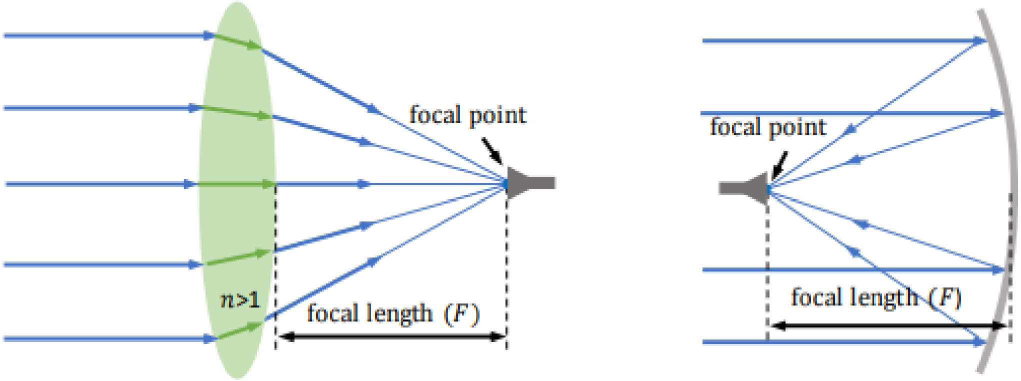

Figure 16: (a) Dielectric Lens (b) Reflector [30]

With the advancement in technologies and the developments in planar antennas, the use of dielectric lenses and reflectors is reduced since they are heavy, bulky, and costly. Planar antennas such as microstrip patch antennas are less costly, compact, and easy to fabricate and were introduced for near-field focusing operations. Planar antenna array by exploiting the phases at each element made it possible to have a constructive interference at the focal point and hence focus the radiation pattern. One of the major advantages of planar antenna arrays is that you do not need any secondary setup such as a lens or reflector to focus the radiated fields.

3.2 Near-field Focusing Mechanism

To understand the phenomenon of near-field focusing, consider an 8×8 planar microstrip patch antenna array as shown in Figure 17. The elements of the array lie in the x-y plane and are equally spaced along both directions. The antenna array is supposed to converge the radiated fields at a predefined point called the focal point i.e. F. The point F is positioned at $(0, 0, z_f)$. Based on the previous discussion, the radiated fields from the antenna array will focus only in the case that the radiated fields from the individual elements of the array have the same phases at the focal point. The same phases at the focal point will lead to constructive interference at the focal point and fields will sum up forming a focused radiated spot.

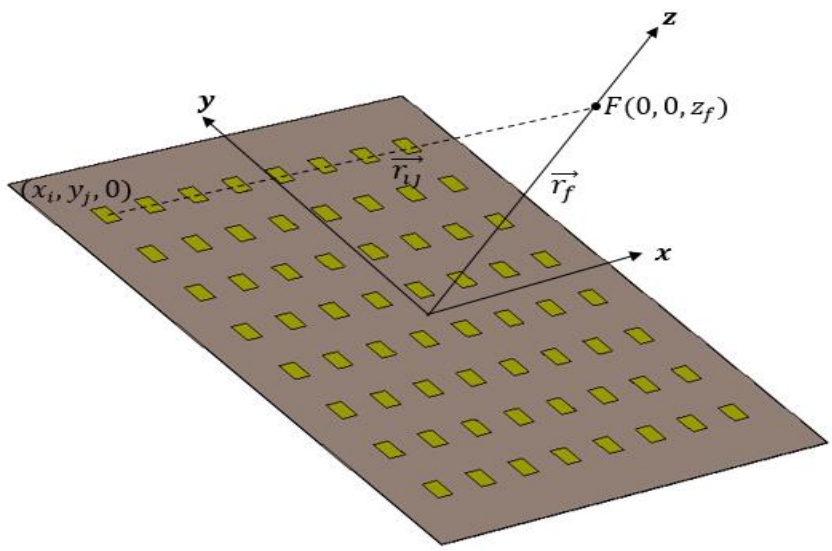

Figure 17: 8 × 8 Near-field Focused Patch Antenna Array

The elements in the array are placed in the x-y plane with coordinates $(x_i\ , y_j\ , 0)$ for the i, j^{th} element of the array. The distance between the i, j^{th} element of the array and the focal point is $\overrightarrow{r_{ij}}$. Where $\overrightarrow{r_f}$ is the distance from the origin of the array to the focal point. For a fixed focal point $\overrightarrow{r_f}$ is constant while $\overrightarrow{r_{ij}}$ will be different for different elements based on their position in the array. If all the elements in the array are excited with the same phase at the antenna aperture, they will not have the same phase at the focal point. This is due to the fact that the elements located at different positions have different distances from the focal point. A mechanism should be applied so that the elements that are closer to the focal point in terms of distance are delayed so that the field lines from all the elements reach the focal point at the same time. In other words, when the field lines from each element in the array reach the focal point, they must have the same phase and hence will sum up to form a converged spot. The delay in time depends upon the difference in distance between the individual elements of the array to a reference element. The conjugate phase approach [31] is a technique to calculate a set of phases in that the element in the array is required to be in phase at the focal point. The conjugate phase distribution is given as under;

$$\Phi_{ij} = k \times \left\| \overrightarrow{r_{ij}} - \overrightarrow{r_f} \right\|_2 \quad (3.2)$$

Where, Φ_{ij} is the phase in degrees required for i, j^{th} element of the array, $k = \frac{2\pi}{\lambda}$ and $\|.\|_2$ is the Euclidean distance. Conjugate phase distribution can also be expressed in the following form for the antenna array in Figure 17;

$$\Phi_{ij} = \frac{2\pi}{\lambda} \times \left(\sqrt{\left((x_i - 0)^2 + (y_j - 0)^2 + (0 - z_f)^2\right)} - z_f \right) \quad (3.3)$$

3.3 Near-field Focusing Patch Antenna Array Design

Figure 18 shows a 4×4 rectangular patch antenna array in the x-y plane which has been presented to focus the radiated field at a predetermined point in the near-field at 2.4 GHz [9]. The said system uses the quadratic phase distribution in equation 3.3 to find the phases required for each element to be in phase at the focal point.

Rectangular microstrip patch antennas printed on an FR-4 dielectric substrate ($\varepsilon_r = 4.3$) with thickness 0.16 cm with length and width of single element patch is 2.9 cm and 2.95 cm respectively. The overall dimension of the array is 40×40 cm^2 with inter-element distance along the x and y direction as 10 cm. The target focal point is chosen to be F(0, 0, 80) cm . The inter-element distance is very crucial and is chosen to have a trade-up between the grating lobe and beamwidth. The said inter-element distance will make sure the radiation pattern will have acceptable levels of grating lobes and beamwidth.

Using the equation of quadratic phase distribution based on the given information i.e., location of each element in the array and the focal point, the phases required for each element are calculated. These phases are then to be fed to each element, which will make sure that the individual element's radiation at the focal point will sum up.

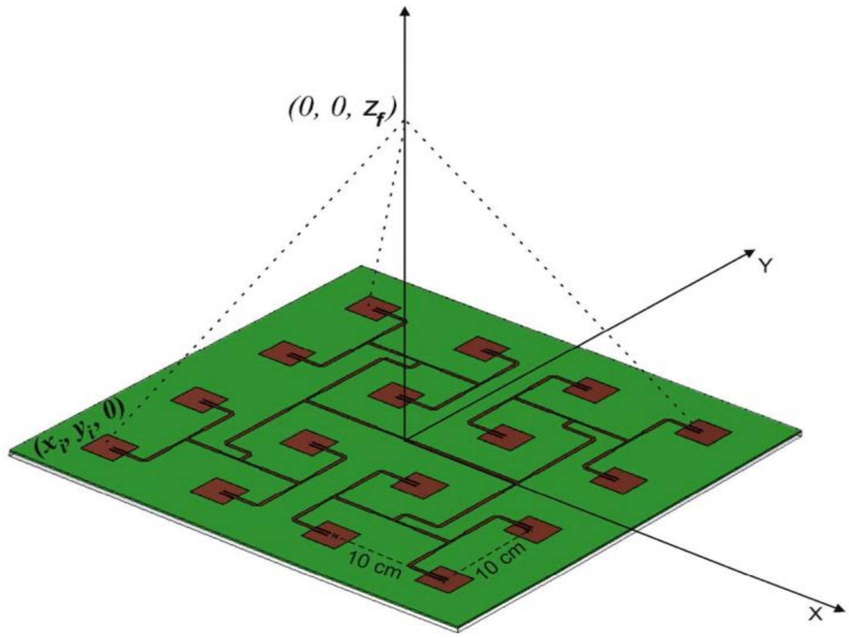

Figure 18: 4 × 4 Near-field Focused Patch Antenna Array [9]

The locations of each element in the array as well as their calculated phase distribution are given in Table 1 and 2 respectively. Elements at the positions given in Table 1 are fed with their respective phase, which means that elements of the array are supposed to be delayed to a reference element which is the farthest of all elements. In this way, at the focal point, the individual contribution of each element will reach at the same time.

Table 1: Array Elements Positions in mm

y_j \ x_i	**1**	**2**	**3**	**4**
1	(-150, 150)	(-50, 150)	(50, 150)	(150, 150)
2	(-150, 50)	(-50, 50)	(50, 50)	(150, 50)
3	(-150, -50)	(-50, -50)	(50, -50)	(150, -50)
4	(-150, -150)	(-50, -150)	(50, -150)	(150, -150)

Table 2: Phase Distribution for Array Elements in Degrees

$\Phi_{i,j}$	**1**	**2**	**3**	**4**
1	79.6	44.6	44.6	79.6
2	44.6	8.9	8.9	44.6
3	44.6	8.9	8.9	44.6
4	79.6	44.6	44.6	79.6

The phase delay can be introduced through the feed line connected to each element. A microstrip feed line is used here based on the Wilkinson power divider, which divides a single input microwave source into 16 feed lines having a uniform magnitude and the phases can be changed by changing the length of the feedline to each element. Elements that are near the focal point would have a longer transmission line as compared to the one away from the focal point to compensate for the delay and have phase equality.

3.3.1 Results and Discussion

Figure 19 shows the return loss of the system, which depicts that the return loss is well below the acceptable range at the design frequency. Figure 20 elaborates on the normalized power density along the z-axis (normal to the array aperture) passing through the focal point. Both the simulated and measured results are provided. It can be observed there that although the target focal point was 80 cm along the z-axis the maximum power density lies at a point between the antenna array aperture and the focal point. This point is called as maximum power point. The maximum power happens to be at a distance of about 32 cm along the z-axis. The difference between the focal point and the maximum power point is called as focal shift. The focal shift in this case is about 48 cm.

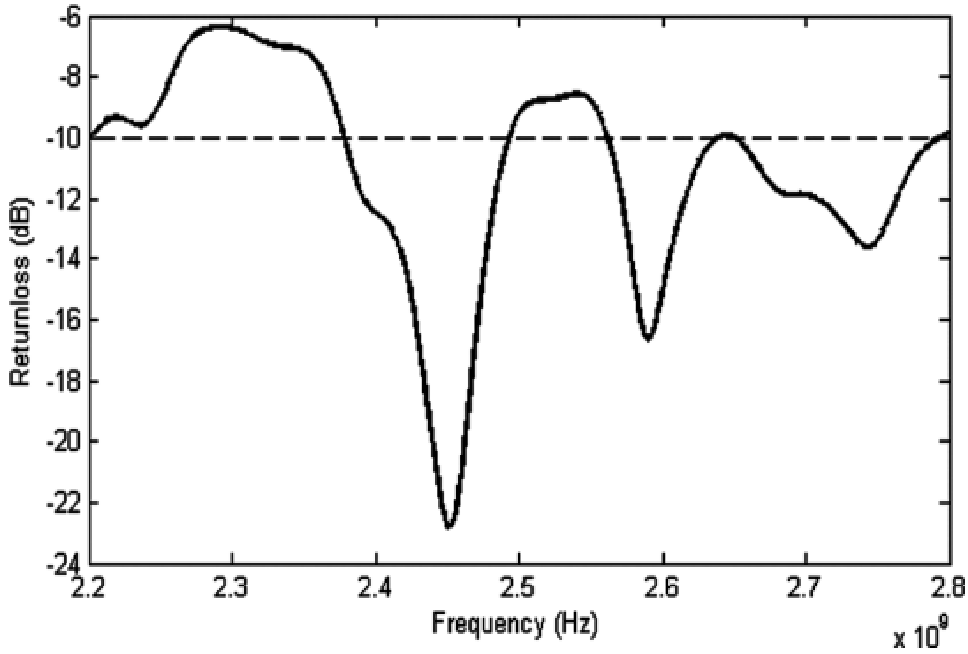

Figure 19: Return Loss of Antenna Array [9]

The reason for the focal shift is the field spreading factor in the near-field which happens to be about $\frac{1}{r^3}$. Therefore in some applications, the focal point chosen before the design is an approximation to where the maximum power point will lie, and later on, the maximum power point can be selected as the focal point. [32] provides a detailed study of the relationship between the focal point and maximum power point along with techniques on how to reduce the focal shift. The depth of focus is found to be about 45 cm.

The depth of focus is an associated phenomenon with focused antennas which means the points along the focal plane where the power level is half of the maximum power. At both sides of the maximum power point, the total distance at which the maximum power level is reduced by half will be the width of focus. It gives a limit to the focusing operations.

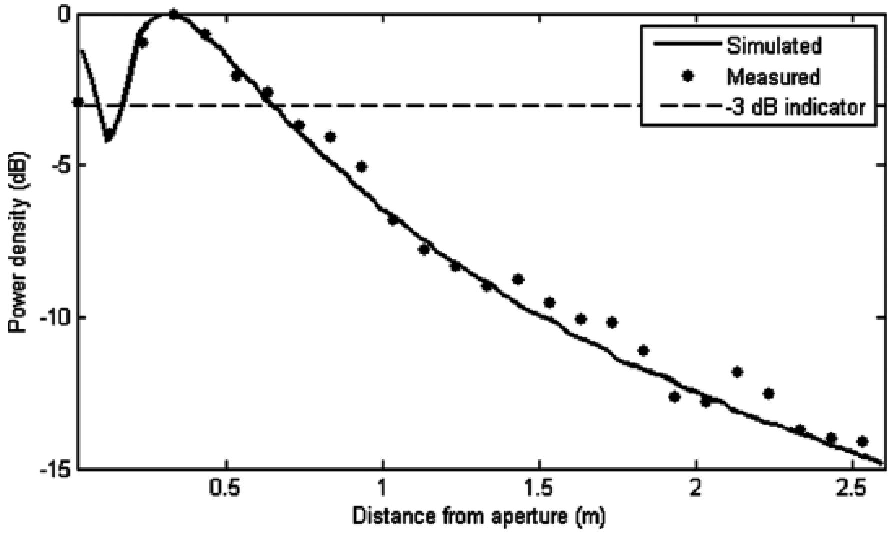

Figure 20: Normalized Power Density along $(0, 0, z_f)$ [9]

The most important phenomenon of the focused antennas is the width of focusing. The width of focusing also called the size of the focused spot is the 3 dB size of the focused radiations. The size of the focused spot is very crucial and it varies from application to application. The width of focus at the maximum power point and focal point is 10×10 cm^2 and 21×21 cm^2 respectively. The normalized field intensities along both the maximum power point and the focal point are given as under;

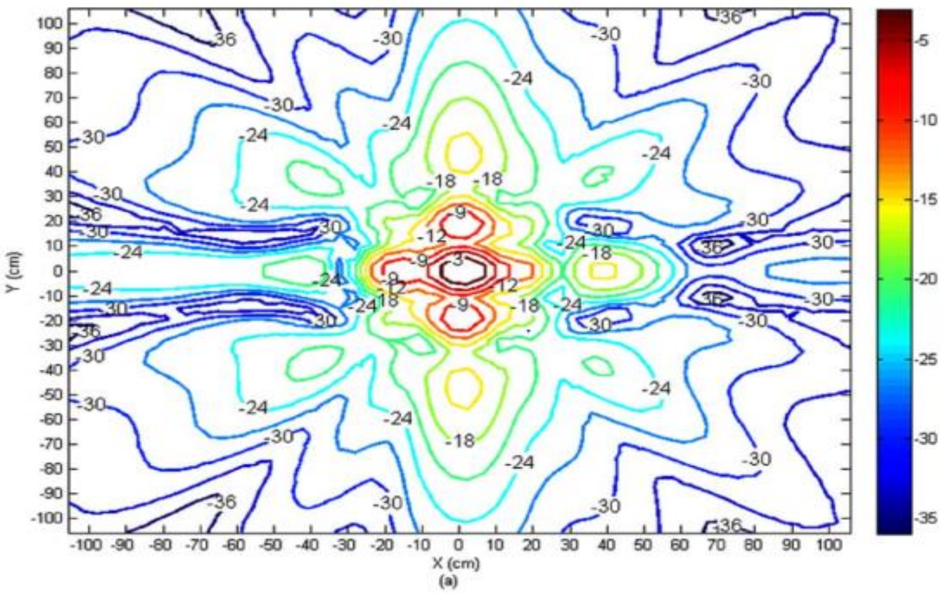

Figure 21: Normalized Power Density at (x, y, 32) cm [9]

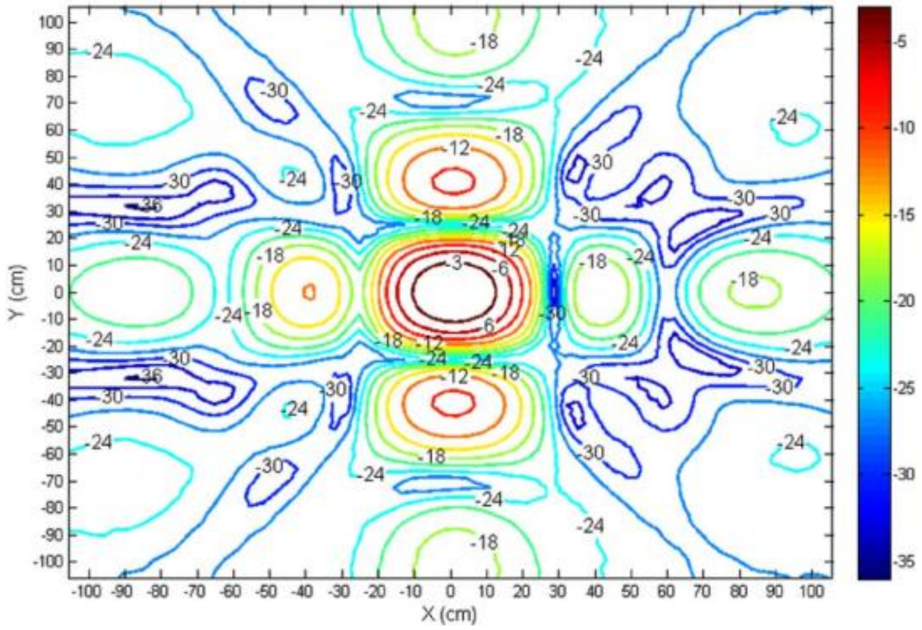

Figure 22: Normalized power density at (x, y, 80) cm [9]

The discussed design along with results gives a detailed picture of how the near-field focusing can be achieved and what are the associated phenomenon with near-field focusing.

Chapter 4

NEAR-FIELD FOCUSED MICROSTRIP PATCH ANTENNA ARRAY CHARACTERISTICS ENHANCEMENT WITH PARASITIC PATCH ELEMENTS

4.1 Introduction

Patch antenna has been one of the first choices for several applications due to their versatile characteristics. Due to their low cost, printable properties, and their integration with other components, patch antennas are highly demanded antennas. In this thesis, the main focus is on applications related to the near-field focusing. Whether it is for industry, military, or many other applications, the main goal of the near-field focusing is to converge the radiated field at a pre-determined point away from the antenna array aperture. As a result of focusing the fields at a certain spot or point, it is obvious that the intensity of the focused fields would be higher compared to that of unfocused fields. Since patch antennas are low-profile antennas and their power handling capabilities are low. There might be a possibility that even after focusing the radiated fields, the field intensity at the focal point is not up to the mark, due to small input power. Either the input power needs to be increased or the antenna array needs to be modified in such a way that the required amount of power is achieved at the focal point.

In [7], a near-field focused patch antenna array has been designed for use in industrial applications. An industry produces certain materials, which are small in size. The near-field focused patch antenna array focuses the radiated fields at the point, where the material's quality is tested. The more the radiated power converges, the more intense the fields at the point of interest. There a certain key factors, in deciding upon the quality of the focus, for example, the focal distance and the size of the array. If the focal point is close to the antenna aperture, the radiated fields converge to form a high-intensity focused spot. The fact is that, as compared to the far field, where the fields spread by a factor of $\frac{1}{r^2}$, this rate is much higher in the case of near-field. But choosing a focal point, most of the time depends upon the application or the setup, where the antenna array needs to be used. In the case of testing material quality in the industry, the existing setup might not allow one to put the antenna array at the point of one's choice. There is a lot of other machinery around and safety factors are to be considered. In the said case, if the antenna array is kept at a distance from the point of interest, i.e., in the near-field but not very close, the focused fields might not be enough strong to perform efficiently.

The second important factor is the size of the antenna array. The size of the antenna array does not solely mean how small or large the antenna array is but also the number of antenna elements needs to be accounted for. For fixed inter-element spacing, the magnitude of radiated fields from a 4 elements array would be much less than that of 16 elements. The more the number of elements, the bigger and larger the array would become and it would require more space to be put in. As technology advances, majority of the modern-day equipment uses compact and small-size antennas and arrays. The said problem is not only associated with industrial applications of near-field focusing but other applications do face such challenges as well. In microwave-induced hyperthermia, the diseased part of the body or tissue is exposed to high-intensity and focused radiated fields, so that it can be heated up. Within the safety limits of the human body, what is the intensity of the focused fields at the focal point, depends upon how close or far is the focal point, how many elements are in the antenna array and what is the input power.

In a specific scenario, where the focal distance is large, the antenna array is small in size, and the low power handling capability of patch antennas is, it is required to modify the existing antenna array system in such a way that the deficiencies are covered. In the past, there were several techniques used in both near and far fields to improve the antenna's performance, such as increasing the directivity, and gain. In [35-36], techniques such as increasing the number of array elements, using dielectric substrates of different sizes, and Electromagnetic bandgap structure (EBG) have been used to increase the gain of the antenna array. Although the mentioned techniques are applied in the far field, they work in the near field as well. Our concern here is not only the near-field but the focus as well. The use of parasitic elements along with the driven elements is also encouraged in the literature, to raise the intensity of radiated fields [37]. In this technique, parasitic elements i.e., passive elements are placed on top of the driven elements of the array. The radiated fields by the driven elements are fed to the parasitic elements and it gets enhanced by a certain factor. The beauty of the said technique is that it does not alter the characteristics of the driven elements of the array. In this chapter, a near-field focused patch antenna array system with the inclusion of parasitic elements is proposed to further increase the intensity of the radiated focused fields. A conventional 4×4, patch antenna array is designed to focus the radiated fields at a certain point in the near-field. The NFF antenna array uses the quadratic phase distribution, discussed in Chapter 3 for achieving focusing characteristics. Once the focus is achieved, a layer of parasitic elements is placed in a specific manner, so that the focused radiated fields are multiplied by a factor.

4.2 Proposed Antenna Array Design

The proposed design can be divided into two parts, the near-field focused patch antenna array and the inclusion of parasitic patch elements. In the first part, a 16 elements rectangular patch antenna array lying along the x-y plane, has been designed at 2.4 GHz. The focal point chosen for the antenna array to converge the radiated fields is F (0, 0, 800) mm. The dimension of the inset-fed single element of the array is 29×29.5 mm^2, using an FR-4 dielectric substrate of thickness (h_1) as 1.6 mm, loss tangent of 0.023 and permittivity (εr_1) of 4.3 as shown in Figure 24. The dimension of the array aperture is 400×400 mm^2. The inter-element spacing along the x and y axis is 0.8λ (100 mm).

For the proposed antenna array to be able to focus the radiated fields at F (0, 0, 800) mm, a set of phases is calculated from eqn. 8 based on the locations of the elements of the array. The set of phases calculated is shown in Table 3.

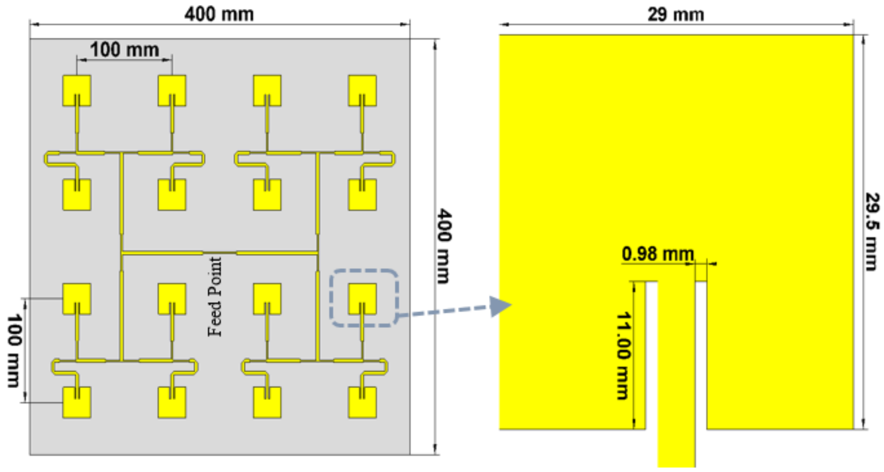

Figure 23: Patch Antenna Array and Single Element of the Proposed Design

Table 3: Phase Distribution for Array Elements in Degrees

$\Phi_{i,j}$	**1**	**2**	**3**	**4**
1	79.6	44.6	44.6	79.6
2	44.6	8.9	8.9	44.6
3	44.6	8.9	8.9	44.6
4	79.6	44.6	44.6	79.6

A corporate feeding method has been used as an excitation feed network. The feed network consists of a microstrip 16-way equal power divider, where at each step a 50Ω microstrip line with a width of 3.065 mm is divided into two equal 50Ω microstrip lines by incorporating a quarter wavelength microstrip line. The impedance of the quarter wavelength line is 70.71 Ω with a thickness of 1.5815 mm and length of 17.72 mm. To avoid any bending loss in the feed network a mitred bend is used in the design. For all the elements to be in phase at the focal point, the length of transmission lines leading to those elements is changed. Elements that are closer to the focal point are delayed, so that all elements have the same phase at the desired focal point. It can be observed in Figure 23, that all elements of the array are not in the same orientation, hence an extra 180 degree phase shift is introduced to those elements that are out of orientation. Furthermore, microstrip mitered bends are used in designing the feed network to minimize any bending loss. The first part of the proposed design is completed here.

The second part of the proposed design is related to the inclusion of parasitic patch elements in the design in part first. The parasitic patch elements will be driven by the near-field focused fields originating from the design in the first part. Figure 24 shows the complete picture of the proposed design, where on top of the driven patches, a dielectric substrate foam of thickness 15 mm (h_2) and permittivity (εr_1) of 1.068 is added. On top of the foam substrate, an FR-4 substrate of thickness 1.6 mm and loss tangent 0.023 is added so that the parasitic patch elements can be etched on. The dimensions of the foam substrate and the FR-4 substrate are the same as the array aperture i.e., 400×400 mm^2. The parasitic patch elements are placed in the same location as the driven elements. The size of the parasitic patch elements is the same as that of driven elements. The thickness of the foam substrate is chosen experimentally, to get optimum results.

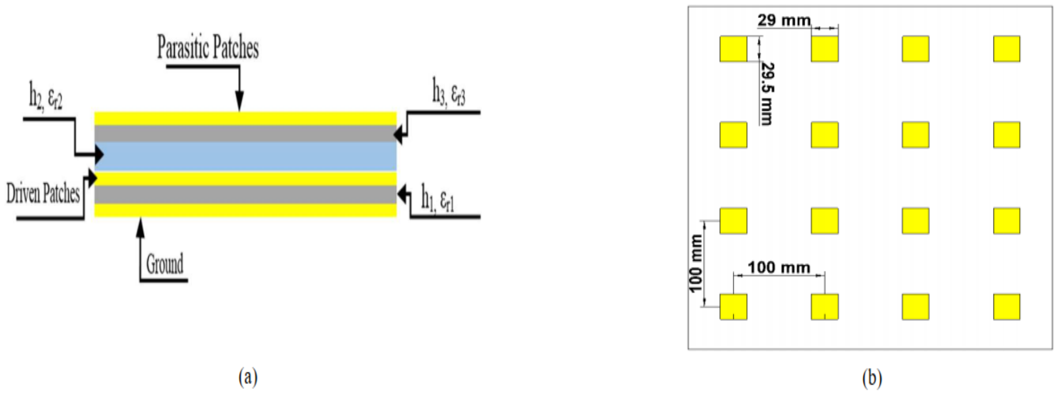

Figure 24: Proposed Design (a) Side View (b) Top View

The driven patch elements fed with certain phase difference compared to each other ensures that the radiated fields are focused at the focal point, while the parasitic patch elements get driven by the focused fields and enhance the intensity of the focused fields at the focal point.

4.3 Results and Discussion

Figure 25 shows the return loss plot of a near-field focused patch antenna array with and without parasitic patch elements. At the designed frequency of 2.4 GHz, the magnitude of the reflection coefficient is in order of less than -30 dB, which confirms a nearly perfect match. There is a very small amount of shift in the return loss plot as the parasitic patches are included, but still, the proposed antenna array design is well-matched at the design frequency.

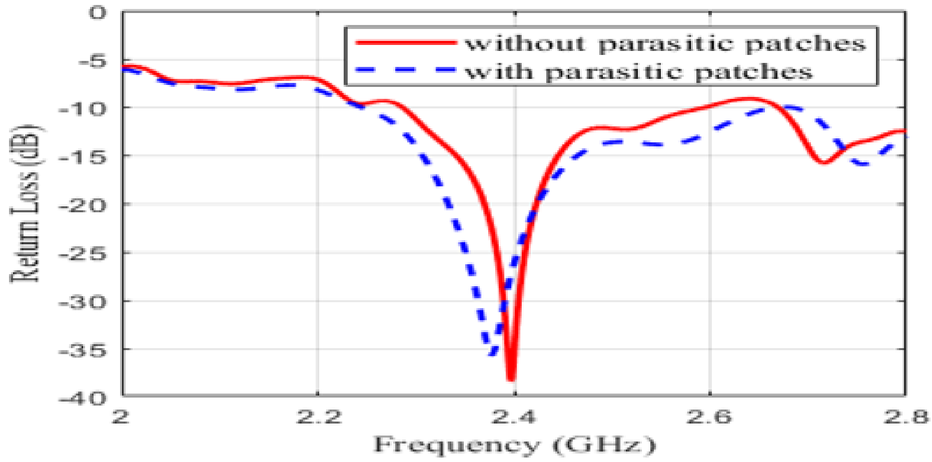

Figure 25: Return Loss of NFF Patch Antenna Array

The normalized E-field versus distance along the focal point is shown in Figure 26. It can be observed from the figure that although the focal point for the proposed system was chosen as F(0, 0, 800) mm, the maximum power happens to be at the point occurring before the focal point i.e., (0, 0, 320) mm. The difference between the focal point and the maximum power point is 480 mm. This difference in focal and the maximum power point is an expected phenomenon associated with near-field focused antennas. At the maximum power point, although the fields are not in phase the magnitudes add up to form a spot behaving as a focal point. In applications, where it is very important to have the maximum power point and focal point as same, either the dimensions of the array should not be very small as compared to the focal distance, or the focal point must be closer to the antenna array aperture. For F to be the focal point and D to be the largest dimension of the array aperture, γ is the deciding parameter for the difference between the focal point and maximum power point, also known as focal shift [31].

$$\gamma = \frac{F}{(\frac{2D^2}{\lambda_0})} \quad (4.1)$$

For an antenna array to be in the near-field, γ should be less than 1. If the focal point is not considerably larger than the dimension of the array, γ values less than 0.1 show a very good amount of reduction in the focal shift. Here the focal shift is not the primary concern, as at the focal point still there is a good amount of field converging as compared to the unfocused antenna array.

It can be observed from Figure 26, that the maximum power point for both the antenna arrays, with and without parasitic patch elements is the same. With the inclusion of parasitic patch elements, the power levels at both the maximum power point and the focal point are increased by a factor of approximately 4.2 dB. This confirms that without changing the focal point, increasing the number of elements, or increasing the input power, the magnitude of the radiated focused fields can be enhanced for a good amount.

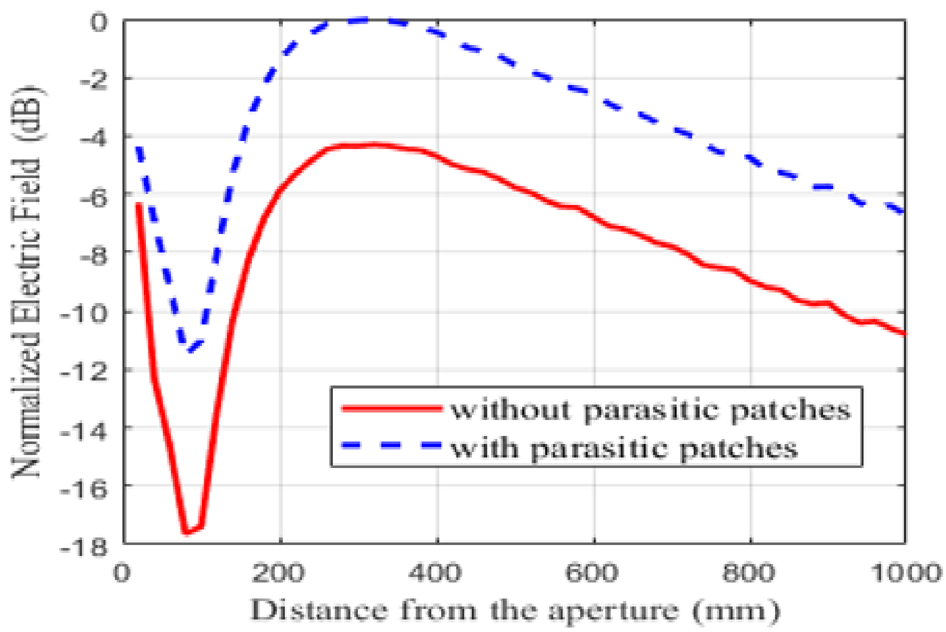

Figure 26: Normalized E-field along (0,0,z)

The normalized E-field in the x-z and y-z plane at the maximum power point and focal point are illustrated in Figures 27 and 28 respectively. The spot size at the maximum power point is 110×110 mm^2, while at the focal point, it is 130×145 mm^2. The spot size of the proposed antenna array agrees well with the theoretical formulation of focused spot size in [32].

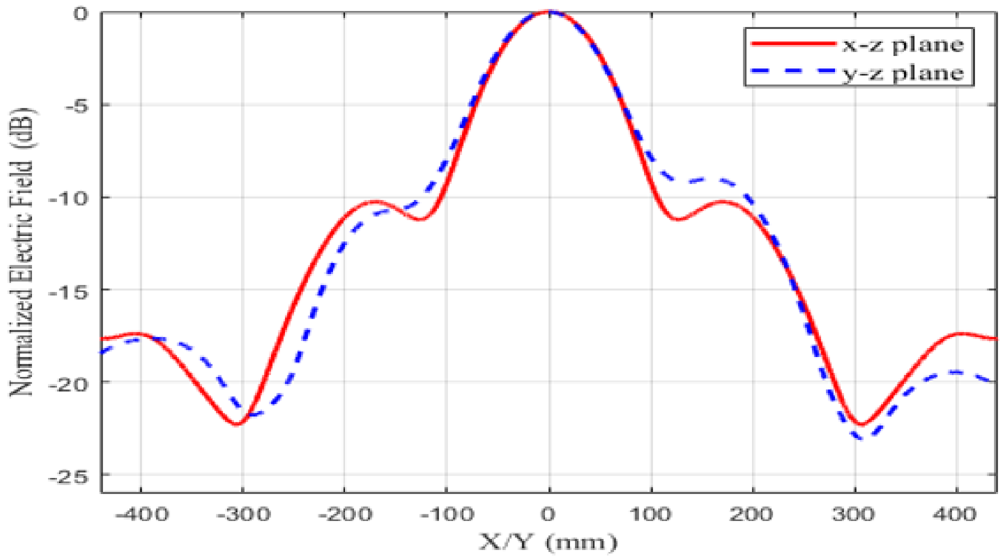

Figure 27: Normalized E-field along x-z and y-z Plane at Peak Power Point

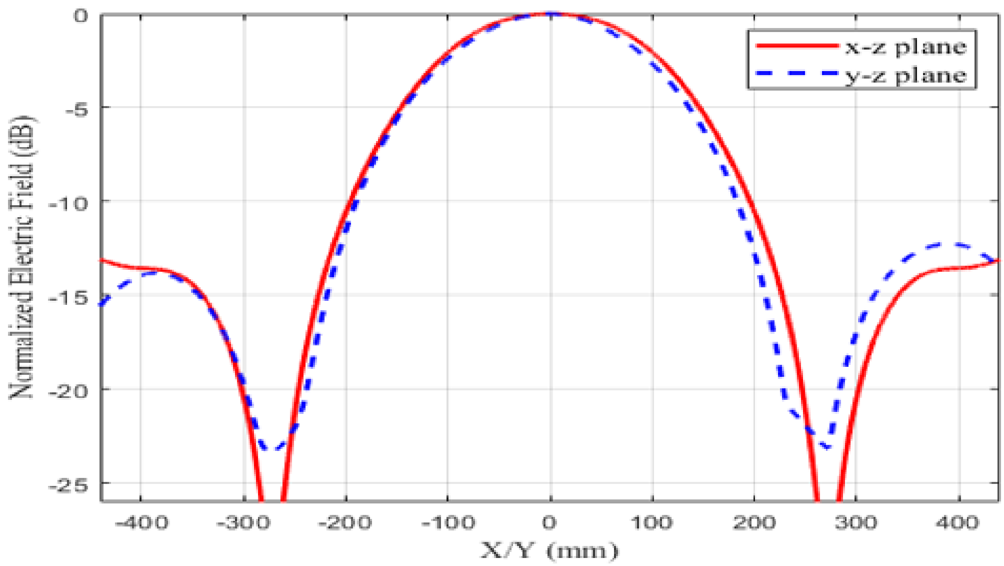

Figure 28: Normalized E-field along x-z and y-z Plane at Focal Point

It can be observed from all of the above-mentioned results that with the inclusion of parasitic patch elements, the focusing characteristics of the patch antenna array do not change. The maximum power point and the spot size remain the same, and the magnitude of the focused power increases by 4.2 dB.

4.4 Conclusion

This chapter proposes a near-field focused patch antenna array with parasitic patch elements to increase the magnitude of the focused radiated power at the focal point. For the enhancement of the focused radiated fields, the antenna array does not alter its basic structure or parameters. The focused radiated fields from the driven elements of the array are fed to the parasitic patch elements and at the focal point, the magnitude of the focused fields is incremented. Results suggest that, in applications, where the focused fields are not up to the mark in terms of intensity, the proposed method can be used instead of altering the basic design parameter of the near-field focused antenna arrays.

Chapter 5

SCANNING OF THE NEAR-FIELD FOCUSED BEAM BY CHANGING FREQUENCY

5.1 Introduction

In the last two chapters, a very detailed explanation of the near-field focusing phenomenon has been presented. The use of near-field focusing varies from application to application. In all the previously mentioned applications, the near-field focusing is achieved at a predefined focal point, which is not dynamic. To change the focal point or focus the radiated fields at a different point, a completely different set of phases needs to be applied or the position of the antenna array be changed by a mean. Providing a completely different set of phases is a very complex job, as the transmission lines leading to the individual elements of the array are printed/etched ones. Once printed or etched, altering them is as complex as designing a whole new antenna array. Changing the physical position of the antenna array is possible through human or machine interaction. In both cases, it is not efficient and accurate to estimate the new focal point.

In several applications, where the focused fields are to be directed at the area of interest, which is much larger as compared to the focused spot or multiple areas need to be scanned. There are several beam scanning techniques used in the past to direct the main beam radiating from an antenna array to a desired direction. Antenna arrays using these techniques are usually divided into two main categories, Dynamic Phase

Arrays, and Fixed Phase Arrays. Electronic beam scanning refers to the change in direction or position of the radiated beam in a certain direction without moving the antenna array mechanically (Dynamic Phase Arrays) or instead of changing the beam direction, changing the position of the antenna array (Fixed Phase Array).

In [38], a 10-element linear antenna array has been designed with the addition of parasitic elements on top of them. The beam scanning of around 14.5 degrees is achieved by activating different combinations of driven and parasitic elements at a certain time. This specific antenna array system does not require any phase shifter network. A linear array of patch antennas was designed for radar in space applications [39], along with a printed phase-shifting network on a dielectric substrate. The said phase shifting network resulted in beam scanning of approximately 10 degrees. Electronic beam steering via antenna arrays was achieved in [40], by forming large arrays of antennas in parabolic shape. Activating a specific group of elements of the array would determine the direction of the main beam.

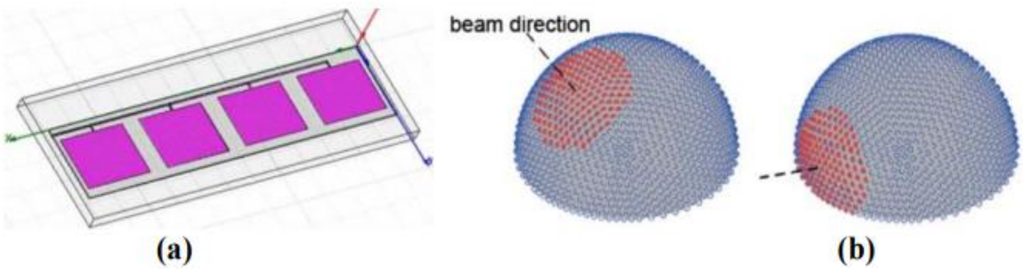

Figure 29: Antenna Arrays by (a) Goel [38] and (b) Cheng [39]

Phase locked loop circuit is utilized in [41], to control the phases of the patch antenna array to carry out beam scanning. All the mentioned techniques are used to steer the beam in a certain direction but none of them discusses the steering of a beam in a certain direction at a certain point i.e., a focal point.

A near-field focused transmitter antenna array can be used for wireless power transmission to focus the radiated fields at a point, where the target device exists. The target device uses energy harvesting circuits to convert the radio frequencies into useful energy. The focused beam can be scanned in a certain direction to cover more than one target device. The proposed idea is more environment friendly as it focuses the radiated fields at a spot-limited region, unlike conventional beam steering systems which steer the beam at a certain angle with low efficiency and notable air pollution.
In industrial applications, near-field focusing is used for non-destructive material inspection and testing. Material under the test is exposed to the near-field focused beam to inspect and deduct various properties of the material under test, e.g. Moisture. In the case of a large region under the test, the focused beam can be scanned in a certain direction and the whole region can be inspected in that way. The advantage of the proposed method is that it is non-destructive and the required properties can be acquired without breaking or physically damaging the material under test.

In this chapter, a novel near-field focused beam scanning technique is introduced, that does not require any dynamic phase shifting network or changing the position of the antenna array. The proposed antenna array system can focus the radiated fields at a predetermined point and then move the focused beam as a function of frequency. Just by changing the frequency, the focused beam can be moved in a certain direction.

5.2 Methodology

5.2.1 The Method

The near-field focused beam scanning array proposed in this chapter is an antenna array that converges the radiated fields at a focal point and then by variation in frequency, the focused beam or spot is steered in a certain direction. The methodology can be explained by using an antenna array shown in Figure 30. The antenna array lying in the x-y plane is supposed to focus the radiated fields at point $F\ (0, 0, z_f)$ i.e., the focal point in the near-field.

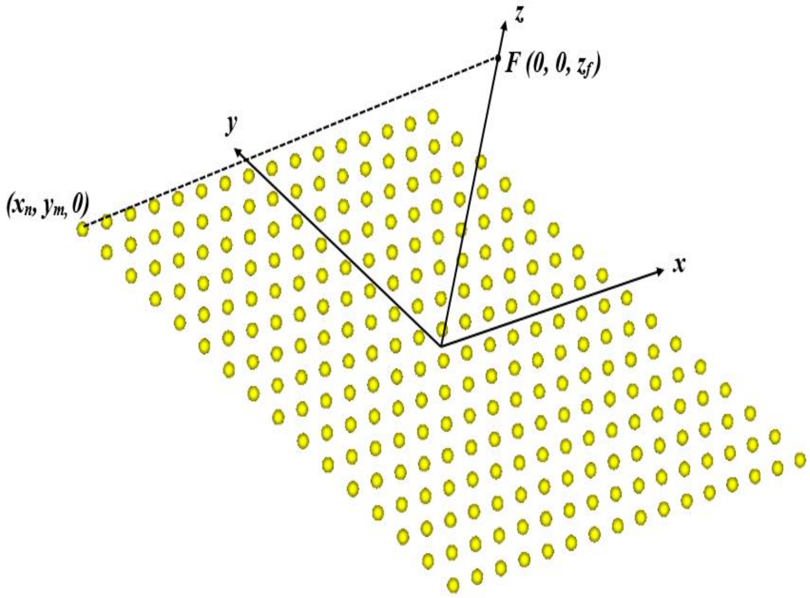

Figure 30: Near-field Focused Antenna Array

As discussed in the last chapters, for this array to direct the radiated fields at the focal point, the individual elements of the array must be fed with a calculated phase shift to a reference.

Based on the position of the element and the focal point, a phase distribution can be obtained using the equation below.

$$\Phi_{n,m} = k \times \left(\sqrt{\left((x_n)^2 + (y_m)^2 + (z_f)^2\right)} - z_f \right) \tag{5.1}$$

x_n, y_m is the (n,m)th element's position. k is the wavenumber at the design frequency f. For the focused field to be scanned, a direction must be chosen in which the scanning should be done. Figure 31 shows a section of the above-mentioned array. The array is a line array at x=constant plane. Since x is constant here, it means the scanning is to be done along the y-axis. $\overline{OF}$ is the distance between the focal point from the origin. The distance between the $(n,m)^{th}$ element of the array and the focal point is $\overline{PF_{n,m}}$. w_{nm}, is the length of the transmission line for $(n,m)^{th}$ element, equivalent to the $\phi_{n,m}$.

The relationship between $w_{n,m}$ and $\phi_{n,m}$ is given in equation 5.2.

$$\phi_{n,m} = \frac{2\pi}{\lambda} w_{n,m} \tag{5.2}$$

The phase shift or set of phases applied to individual elements is achieved by using different lengths of transmission lines $w_{n,m}$.

$$w_{n,m} + \overline{PF_{n,m}} = w_0 + \overline{OF}, \tag{5.3}$$

where,

$$\overline{PF_{n,m}} = \sqrt{{x_n}^2 + {y_m}^2 + {z_f}^2}, \tag{5.4}$$

$$\overline{OF} = z_f. \tag{5.5}$$

For phases to be compared, an element is supposed to be considered as the reference point, usually the element at the origin or close to the origin. w_0 is the length of the reference element, and all the other $w_{n,m}$ are calculated about it. Once equation 5.3 is satisfied, the antenna array is a near-field focused array but with a fixed focal point.

To introduce the phenomenon of beam scanning in the y-direction as a function of frequency, another set of transmission lines is to be added at each level (m) of the array along the y-direction. In the proposed technique, extra transmission line lengths equivalent to multiples of one wavelength are added up to the element of the array at each level (m). These extra transmission lines are in order of full wavelength at the design frequency, so it does not effect the near-field focusing. Transmission line lengths equivalent to $(m\text{-}1)\lambda_0$ are added, where m represents each level of elements along the y-axis of the array. The bottom-most line array along the y-axis is considered as m=1, and so on. The next line array along the y-axis is m=2 and the total difference between the bottom-most and the successive level is one wavelength. Similarly, each successive level is shifted from its previous one by a difference of one wavelength. For a 16×16, antenna array, there are a total of 16 levels along the y direction, where the bottom one can be considered as m=1 and the top one as m=16.

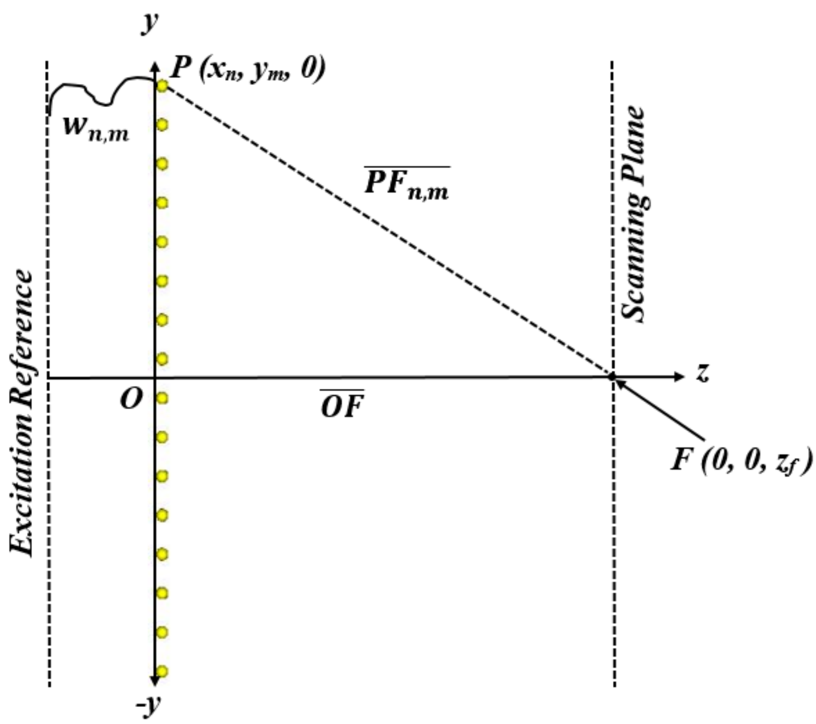

Figure 31: The Geometry of the Focusing Antenna Array

At the design frequency, the phase difference between the elements of the array at each successive level is one wavelength, i.e., 360 degrees. As the frequency changes, the phase difference is not 360 degrees anymore. For instance, if the frequency is increased, the extra transmission line lengths are more than one wavelength long, which in turn produces a phase difference of more than 360 degrees. The elements of the array at each successive level will have a progressive phase difference of more than a wavelength. Defending upon the phase difference, the focused beam is shifted in a certain direction. As the frequency is increased more, the phase difference gets bigger and the focused beam will move further.

5.2.2 Demonstrating the Movement of the Beam

A 16×16 antenna array of isotropic radiators is used to demonstrate the phenomenon of the movement of the focused array antenna. The elements of this antenna are point radiators and the design frequency is 2.4 GHz. The separation between the elements is 87.5mm in both x and y-directions. The focal point is $F\left(0, 0, z_f\right)$, with $z_f = 1250$ mm. The simulation study is carried out in Matlab.

Based on the location or position of the individual elements, $w_{n,m}$ length of transmission lines is made so that the elements add up in the same phase at the focal point. Another set of transmission line lengths equivalent to $m\lambda_0$ at the designed frequency are added at each level along the scanning axis to achieve the scanning properties. At each level, the total transmission line lengths $w'_{n,m}$, (both $w_{n,m}$ and $m\lambda_0$), therefore becomes,

$$w'_{n,m} = w_{n,m} + (m-1)\lambda_0 \tag{5.6}$$

Here, $w_{n,m}$ is used for focusing the radiated fields at the chosen focal point while, $(m-1)\lambda_0$ transmission lines are used for scanning the focused radiated fields. As the $(m-1)\lambda_0$, transmission lines are added only in the y direction, so the scanning is supposed to be happening in the same direction.

Figure 32 shows the normalized E-field plot in dB versus the scanning axis at the focal point for different frequencies. At the designed frequency of 2.4 GHz, the radiated beam is well directed at the focal point i.e., (0, 0, 1250) mm. As the frequency changes above and below the designed frequency, a shift or movement in the main beam is observed. When the frequency is increased, the focused beam moves in the positive y direction. Similarly, when the frequency is decreased, the focused beam moves in the negative y direction. The total scanning distance is the shift in the focused beam until the magnitude of the beam is reduced by 3 dB in both directions.

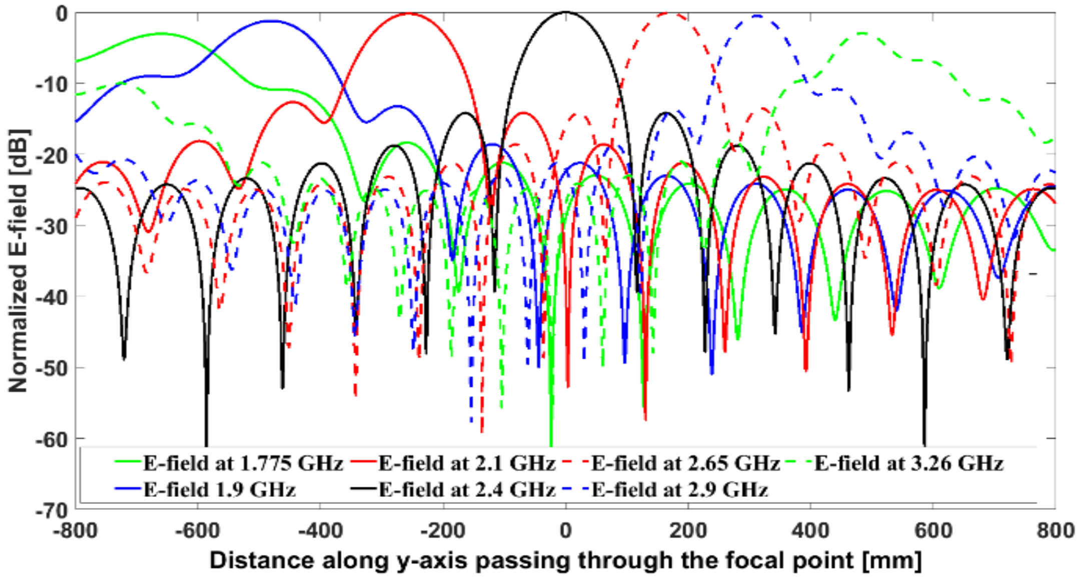

Figure 32: Normalized E-field for 16 × 16 Antenna Array at different Frequencies

The -3 dB points below and above the designed frequency occur at 1.7775 GHz and 3.26 GHz respectively. At 1.775 GHz, the focused beam is at the point (0, -660, 1250) mm, and at 3.26 GHz at point (0, 490, 1250) mm. The total scanning distance along the y-direction is 1150 mm for this particular design.

5.3 Design and Analysis of a Patch Antenna Array

An 8×8 patch antenna array has been designed to implement the frequency scanning of the focused antenna array. As the design of a 16×16 or larger array having varying additional transmission line lengths would be very complex, an 8×8 element array has been chosen for the implementation of the frequency scanning antenna array. To be able to include the additional transmission lines in the design two substrates have been used as shown in Figure 33 having a common ground plane. Figure 33(a) shows the front view of the array design. The patch antenna array is on one substrate and the feed network with the additional transmission lines is on the other substrate (Figure 33(b)). They use a common ground plane [42] as shown in Figure 33(c). The patch antenna elements and ground plane are made up of Copper with 0.035 mm thickness. FR-4 substrate with $\varepsilon_r = 4.3$ with loss tangent 0.0237, having a thickness of 0.8 mm each is chosen for this design. The distance $z_f = 1250$ mm.

The dimension of the inset-fed single element of the array is 29×29.5 mm^2. The dimension of the antenna array aperture is 800×800 mm^2. The transmission line feed network is connected to the patches using conducting pins. The pins are positioned in a way that the lower end of the pins is connected to the feed network, while the upper end of the pin is connected to the patch. The pin position on the patch is selected experimentally based on impedance matching. Regarding the center of the patch antenna, the pin is located at (-6, 2.5) mm. At the points where the pin is passing through the ground plane, a small circular cut of 2.5 mm diameter has been etched so that the ground plane is not shorted with the feed network and the patches.

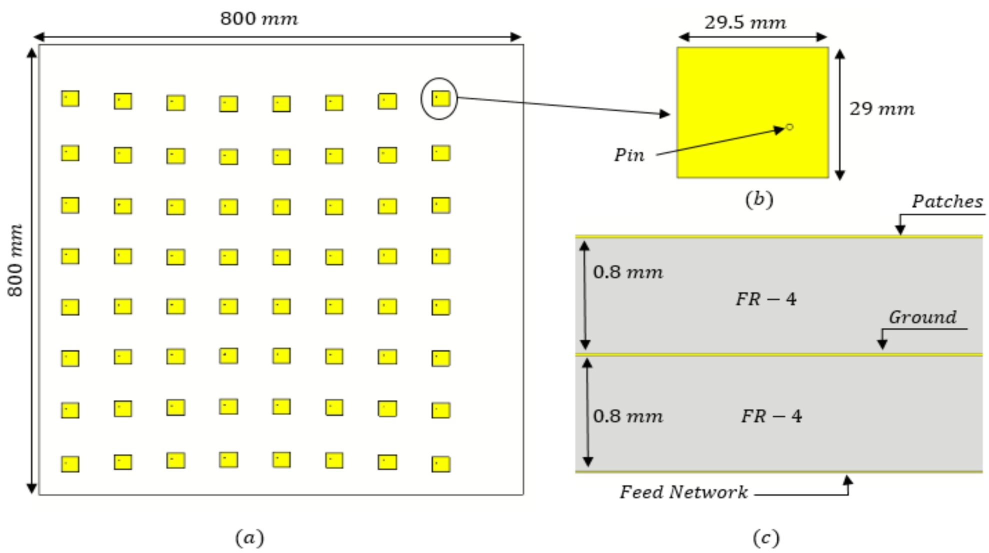

Figure 33: Proposed array design (a) Front view (b) Single element (c) Side view

The set of phases $\phi_{n,m}$ for each element at the design frequency, 2.4 GHz are given in Table 4.

Table 4: Phase Distribution in Degrees

$\boldsymbol{\Phi_{n,m}}$	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
8	222.7	169.3	133.3	115.1	115.1	133.3	169.3	222.7
7	164.4	111.8	76.4	58.5	58.5	76.4	111.8	164.4
6	127	75	39.9	22.2	22.2	39.9	75	127
5	108.7	56.9	22	4.4	4.4	22	56.9	108.7
4	108.7	56.9	22	4.4	4.4	22	56.9	108.7
3	127	75	39.9	22.2	22.2	39.9	75	127
2	164.4	111.8	76.4	58.5	58.5	76.4	111.8	164.4
1	222.7	169.3	133.3	115.1	115.1	133.3	169.3	222.7

$\phi_{n,m}$ are achieved by using the transmission line lengths $w_{n,m}$ given in Table 5.

The additional wavelength λ_g for $(m-1)\lambda_g$ at 2.4 GHz is 67 mm for a 50 Ω microstrip transmission line. This antenna array is designed in CST Studio Suite.

Table 5: Feed Network Line Lengths in mm

$w_{n,m}$	8	7	6	5	4	3	2	1
8	77.32	58.79	46.28	39.98	39.98	46.28	58.79	77.32
7	57.09	38.84	26.52	20.32	20.32	26.52	38.84	57.09
6	44.11	26.03	13.84	07.701	07.701	13.84	26.03	44.11
5	37.76	19.77	07.64	01.53	01.53	07.64	19.77	37.76
4	37.76	19.77	07.64	01.53	01.53	07.64	19.77	37.76
3	44.11	26.03	13.84	07.701	07.701	13.84	26.03	44.11
2	57.09	38.84	26.52	20.32	20.32	26.52	38.84	57.09
1	77.32	58.79	46.28	39.98	39.98	46.28	58.79	77.32

The implementation of the feed network consisting of $w_{n,m}$ and $(m-1)\lambda_g$ for the above design is shown in Figure 34. The feed network uses a microstrip equal power divider circuit of 50 Ω using a quarter wavelength transformer of 70.71 Ω. The thickness of the copper feed network is 0.035 mm. The width of the 50 Ω microstrip line is 3.065 mm. The 70.71 Ω transformer is 1.5815 mm wide and 17.72 mm long.

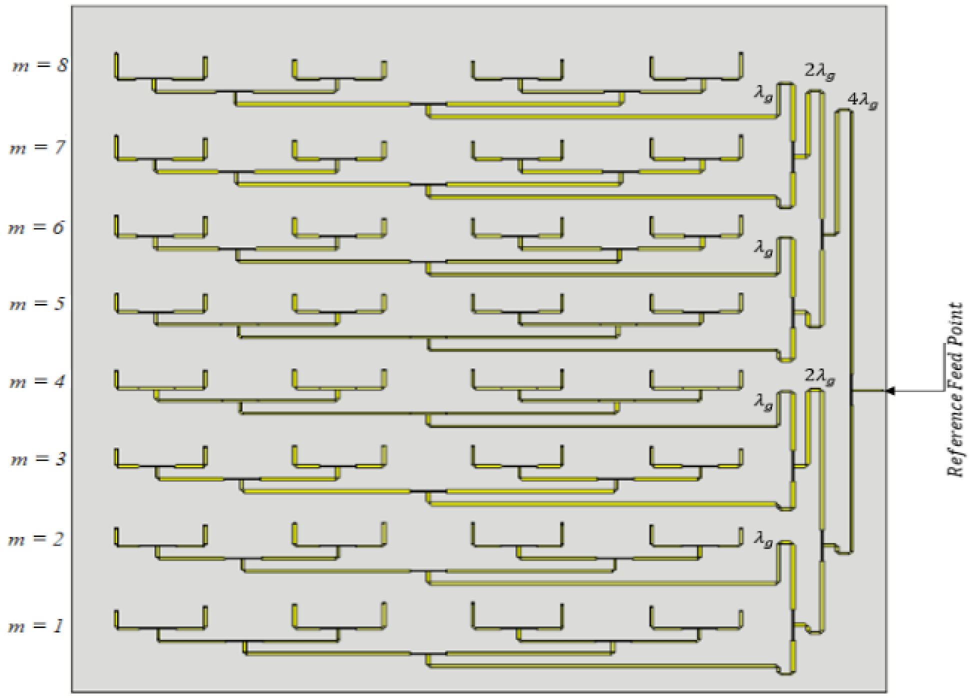

Figure 34: Feed Network and the additional Transmission Lines

To avoid bending losses in the microstrip line, mitered bends are used for 50 Ω microstrip line at 2.4 GHz. Mitered bends are calculated bends, which reduce a specific amount of capacitance from a microstrip line to restore the line impedance to the characteristics impedance after the bend is introduced.

5.4 Results and Discussion

Figure 35 shows the return loss of this 8×8 rectangular patch antenna array system. The magnitude of the return loss is in the order of -30 dB at the center frequency 2.4 GHz and is less than -15 dB over the frequency range of interest.

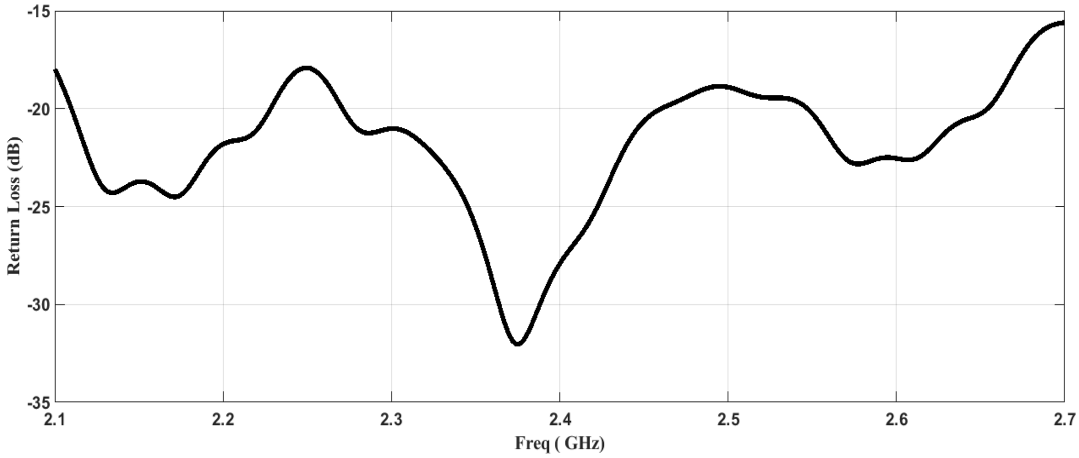

Figure 35: Return Loss of the Designed Antenna Array

The normalized electric field along the x and y directions at the design frequency of 2.4 GHz is shown in Figure 36. In both directions, at 2.4 GHz, the radiated fields are focused at the focal point. The half-power (-3 dB) beamwidth i.e., the spot size of the focused fields is approximately 200 mm in both directions at 2.4 GHz.

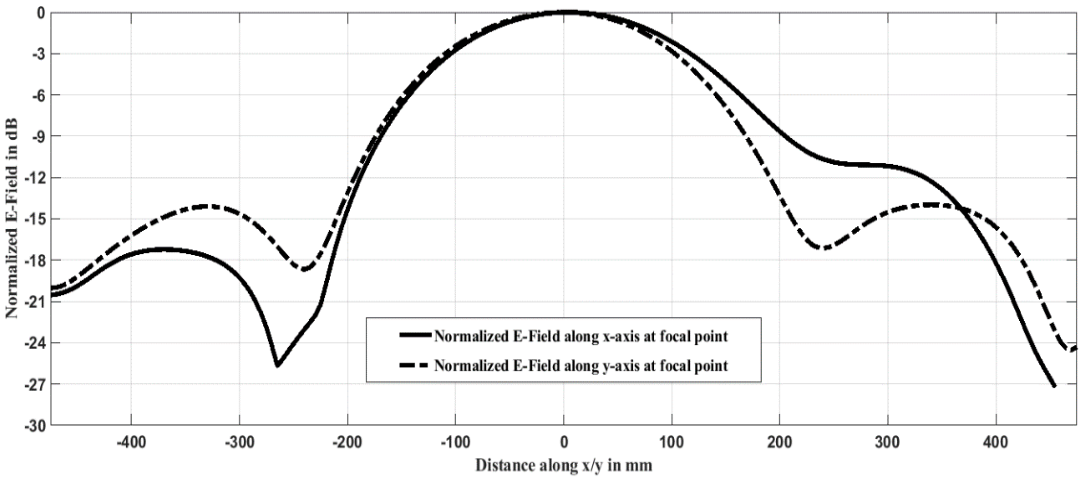

Figure 36: Normalized E-field along x and y Direction at the Focal Point

Figure 37 shows the scanning mechanism, as the frequency is reduced from 2.4 GHz. The shifting of the focused beam along the y-axis is in the negative direction as the frequency is decreased from 2.4 GHz. The peak magnitude of the focused field decreases as it moves away from the focal point. The focused fields reduce to 3 dB of the maximum fields at the frequency of 2.2025 GHz. The -3 dB scanning distance along the negative y direction is 170 mm.

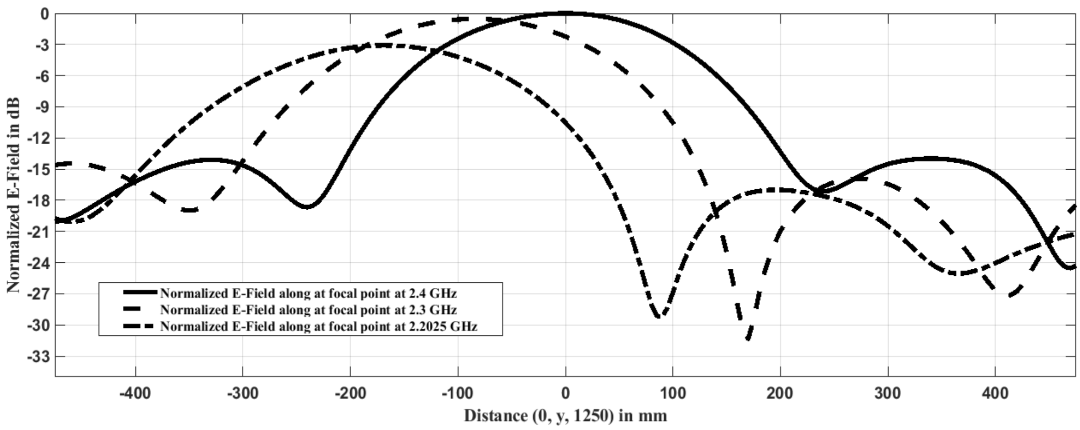

Figure 37: Normalized E-field at the Focal Point for 2.2025 GHz, 2.3 GHz, and 2.4 GHz

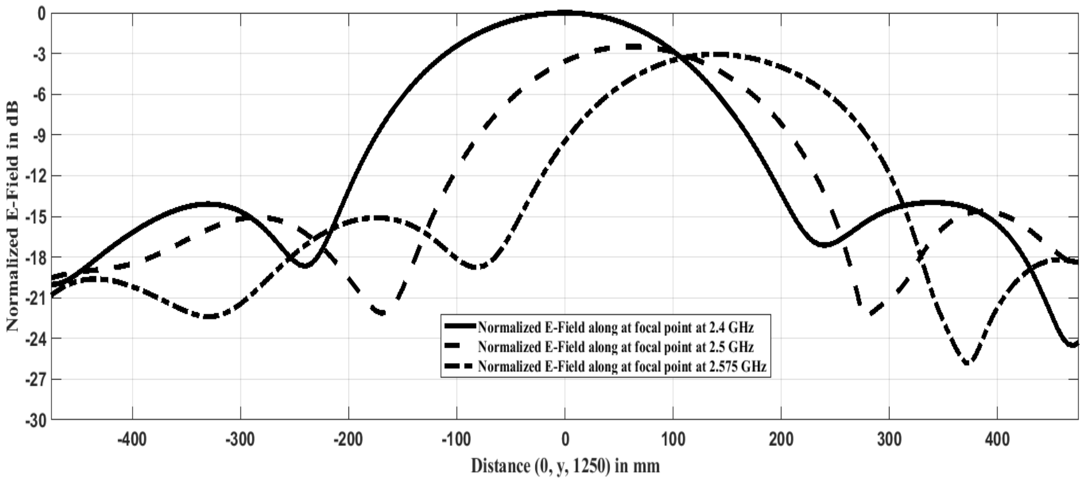

Figure 38: Normalized E-field at the Focal Point for 2.4 GHz, 2.5 GHz, and 2.575 GHz

Similarly, Figure 38 shows the scanning of the focused beam along the positive y direction as the frequency is increased from 2.4 GHz. The peak magnitude of the focused field decreases as it moves away from the focal point. The distance between the peaks at the center frequency (2.4 GHz) and at the frequency (2.575 GHz), where the magnitude of the focused fields reduces by 3 dB is 140 mm. So the total shift of the focused fields along the y-axis, where the power reduces by 3 dB of the peak value at the focal point is approximately 310 mm. These results validate the proposed mechanism of scanning the near-field focused patch antenna array. The scanning distance can be increased by increasing the size of the array as shown in the case of a 16×16 antenna array.

5.5 Conclusion

A new antenna system has been proposed for shifting the focused beam as a function of variation in frequency. The proposed antenna array uses a novel technique of scanning the focused fields as a result of near-field focusing. The antenna system does not require any external phase-shifting mechanism to perform the scanning. The scanning of the focused beam is carried out by changing the frequency of operation.

First, a 16×16 element array with isotropic radiators has been used to demonstrate the movement of the beam with frequency using Matlab. It has been shown that the beam of this antenna system can be shifted by 1150 mm in the focal plane by changing the frequency from 1.775 GHz to 3.26 GHz.

To validate the Matlab simulations, an 8×8 rectangular microstrip patch antenna array has been designed and simulated in CST Studio Suite. A 16×16 patch antenna array with its feed network in CST would require a massive computational domain and the complexity of designing the feed network is a mammoth task. To avoid that situation an 8×8 patch antenna array with the same focal point is designed. The feed network consists of the phase shifts needed for array elements to be in phase at the focal point and the additional transmission line length of multiples of wavelength for scanning are designed at separate dielectric substrates to avoid complexities and coupling. A full wave simulation has been carried out by using CST simulation software. The return loss of this antenna system is satisfactory, being less than -15 dB over the frequency range of interest. The focused beam is moved by 310 mm by changing the frequency from 2.2025 GHz to 2.575 GHz.

Chapter 6

INCREASING THE SCAN DISTANCE OF FREQUENCY SCANNING NEAR-FIELD FOCUSED ARRAY ANTENNAS

6.1 Introduction

In Chapters 4 and 5, the phenomenon of near-field focusing as well as the scanning of the near-field focused beam has been thoroughly explained. With the inclusion of additional transmission lines of $(\mathrm{m} - 1)\lambda$, it was possible to scan the focused beam in a certain direction. The total scan distance was considered as the distance between the two points along the scanning axis, where the magnitude of the focused beam is reduced by 3 dB. The scanning distance here is of great importance and it varies from application to application. For applications, where the region of interest is large and the antenna array is required to scan a large area, the single focal point-focused antenna array might not be sufficient. In the single focal point near-field focused array in Chapter 5, a combination of quadratic phase distribution $\phi_{n,m}$ and additional transmission line of length $(\mathrm{m} - 1)\lambda$ was introduced to focus and shift the beam in the y-direction at a single focal point (0, 0, 1250) mm. However, in the case of a single focal point, as the frequency changes the focused beam moves in the specified direction but the magnitude of the focused beam reduces quickly, resulting in a small scanning distance.

In this chapter, a mechanism for increasing the scanning distance of the near-field focused antenna array is presented by choosing two focal points instead of one. The selection of two focal points will make sure that as the frequency changes, the focused beams will not deteriorate quickly and hence result in an improvement in the scanning distance.

6.2 Methodology

6.2.1 The Method

The methodology of the proposed mechanism can be explained by an antenna array of size n×m lying in the x-y plane as shown in Figure 39. $P_{n,m}$ is a general point on the array, where $(\mathrm{n}, \mathrm{m})^{\mathrm{th}}$ element exists. Here n and m are the indices of the elements of the array in the x and y direction respectively. F1 and F2 are the chosen focal points, where the radiated fields are to be focused first and then moved as a function of frequency. F_1 is chosen to be $(0, -f_d, z_f)$, while F_2 is chosen to be $(0, f_d, z_f)$. F_0 is a point happening just in the middle of F_1 and F_2 i.e., $(0, 0, z_f)$.

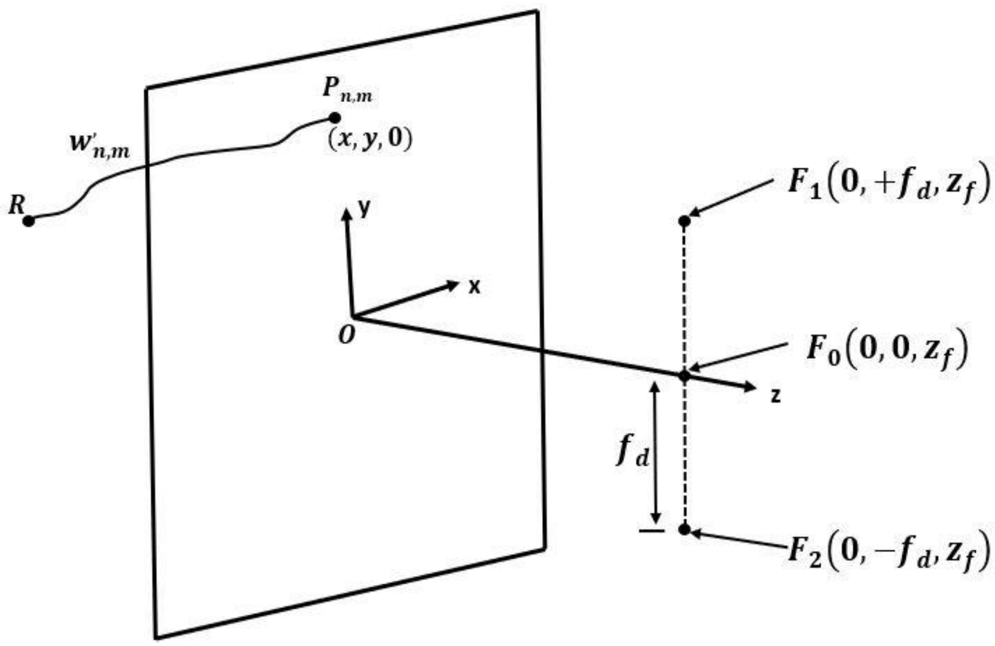

Figure 39: Model of the Two Focal Point Frequency Scanning Array Antenna

$w'_{n,m}$ is the total transmission line length consisting of both $w_{n,m}$ to focus the radiated fields at the focal points and $(\mathrm{m}-1)\lambda_0$ for adding the scanning properties to the antenna array. Where, λ_0 is the wavelength associated with the antenna array design frequency f_0 . Since there are two focal points here, there must be two frequencies at which the beam would be focused at the focal points. f_1 is the frequency at which the radiated fields will be focused at point F_1, while f_2 is the frequency at which the radiated fields will be focused at point F_2. f_1 and f_2 are associated with wavelengths λ_1 and λ_2 , where,

$$\lambda_0 = \frac{\lambda_1 + \lambda_2}{2} \tag{6.1}$$

For the proposed antenna array to be focused at two focal points, the following two equations (6.2 and 6.3) must be satisfied,

$$(w_{n,m} + (m-1)\lambda_o + P\overline{F}_1) - (w_o + O\overline{F}_o) = (m-1)\lambda_1 \tag{6.2}$$

$$(w_{n,m} + (m-1)\lambda_o + PF_2) - (w_o + O\overline{F}_o) = (m-1)\lambda_2 \tag{6.3}$$

Where,

$$P\overline{F}_1 = \sqrt{(x_{n,m})^2 + \left(y_{n,m} - f_o\right)^2 + \left(z_f\right)^2} \tag{6.4}$$

$$P\overline{F}_2 = \sqrt{(x_{n,m})^2 + \left(y_{n,m} + f_o\right)^2 + \left(z_f\right)^2} \tag{6.5}$$

Equations 6.2 and 6.3 must be solved simultaneously, with the known parameters of the antenna array to find two unknowns, i.e., $w_{n,m}$ and $y_{n,m}$. To find the unknown, the position of each element in the x-direction, the wavelengths λ_1 and λ_2 must be known. Usually, the elements in the x-direction are equally spaced. Based on the input parameters to equations 6.2 and 6.3, $y_{n,m}$ which are the calculated positions of the elements in the y-direction, may be non-uniformly spaced. Designing an antenna array with the parameters obtained from the above equations, the radiated fields will be focused at focal point F_1 at the frequency f_1 and at focal point F_2 at the frequency f_2. The $(m-1)\lambda_0$ additional transmission lines will make sure that when the frequency is changed between f_1 and f_2, the focused beam will scan the region between F_1 and F_2. f_0 lies between f_1 and f_2, so at f_0 frequency, the focused beam will be at the center point F_0. Based on the selection of the focal points, inter-element spacing, and dimension of the array, the focused beam at center point F_0 might fall below the acceptable level. The said issue can be resolved by changing the necessary design parameters.

6.2.2 Comparison of Performances of Single and Dual Focal Point Frequency Scanning Near-field Array Antennas

A comparative study of the single focal and dual focal points near-field focused antenna array is presented below. For a single focal point near-field focused antenna array, the mechanism presented in Chapter 5 is applied. 16×16 Isotropic radiator array in Matlab is simulated for single and dual focal point NFF arrays so that their scanning properties can be compared. All the possible necessary parameters are kept the same for a fair comparison.

Both the antenna arrays are designed at the center frequency of 2.4 GHz. The focal point chosen for a single focal point NFF antenna array is F (0, 0, 600) mm. The inter-element spacing in this case is chosen as $0.35\lambda_0$ i.e., 43.75 mm to avoid unwanted grating lobes as the frequency increases. Based on the given information and the positions of the array elements, $w_{n,m}$ and $\phi_{n,m}$ are calculated.

Figure 40 illustrates the normalized E-field versus frequency in the y-direction at z_f for the single focal point array. It can be observed from the figure that at the center frequency of 2.4 GHz, the radiated beam is focused at the focal point F (0, 0, 600) mm. As the frequency varies, a shift in the focused beam is happening in the y-direction depending upon the change in the value of frequency. When the frequency decreases from 2.4 GHz, the focused fields move in the negative y-direction. As the focused fields are moving away from the predetermined focal point, it is expected that the power level will go down or unwanted levels of grating lobes can be experienced. At a frequency of 1.97 GHz, the magnitude of the focused beam reduces to 3 dB of the maximum field at focal point F. This is the stoppage point, any more shift in the focused beam will be meaningless as the beam loses half of its magnitude. It covers a distance of around -475 mm in the y-direction, i.e., at point (0, -475, 600) mm. Similarly, when the frequency is raised above 2.4 GHz, the focused beam shifts towards the positive y-direction. At 2.7 GHz, although the magnitude of the E-field reduces only by approximately 1 dB, high levels of grating lobes are experienced. At point (0, 226, 600) mm, the magnitude of the grating lobes is more than 10 dB.

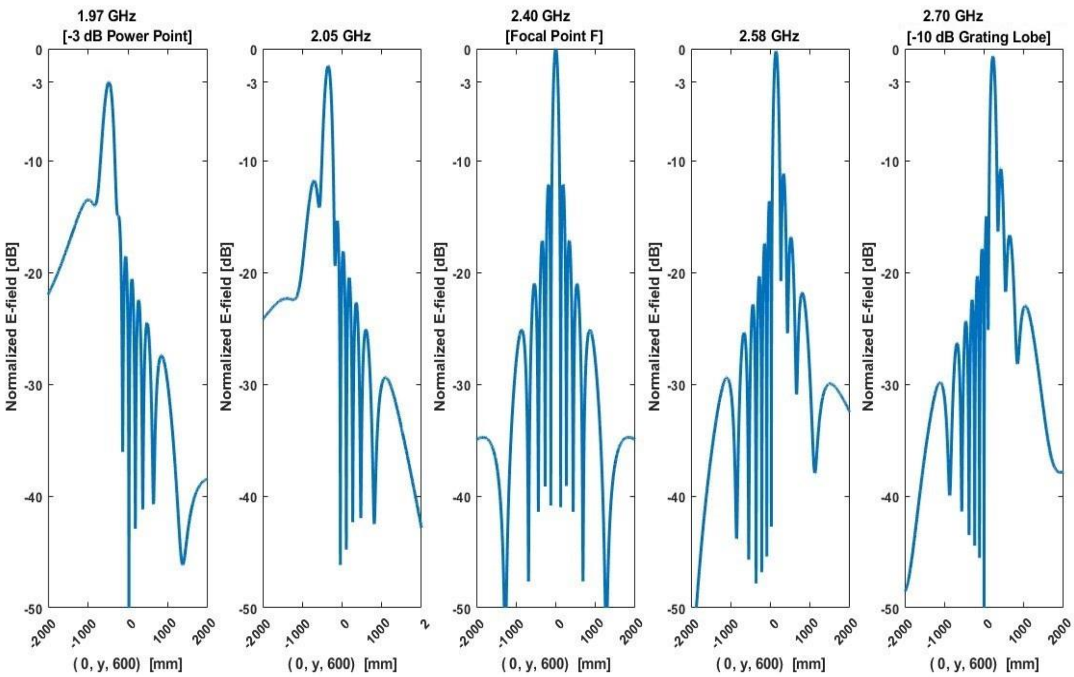

Figure 39: Single Focal Point 16 × 16 Near-field Focused Antenna Array

The total scanning distance for a single focal point NFF 16×16 isotropic radiator array is approximately 700 mm along the y-direction. Similarly, a 16×16 isotropic radiator array at 2.4 GHz is simulated in Matlab to show the mechanism of a dual focal point near-field focused antenna array. F_1 (0, -350, 600) mm and F_2 (0, 350, 600) mm are chosen as the two focal points equidistant from the center point F_0 (0, 0, 600) mm. F_0 is not a focal point but a point lying between F_1 and F_2, where the radiated fields are expected to be at 2.4 GHz. The inter-element spacing along the x-direction is chosen as $0.35\lambda_0$ i.e., 43.75 mm, while the positions for the elements in the y-direction will be calculated from equations 6.2 and 6.3. Based on the given information and the positions of array elements, $w_{n,m}$ and $\phi_{n,m}$ are calculated. For the calculated $w_{n,m}$ and $(m-1)\lambda_0$ additional transmission lines, the proposed antenna array will be able to focus the radiated fields at F_1 when the frequency is f_1, and at F_2, when the frequency is f_2. At the center frequency of f_0, the radiated fields will be at point F_0. As the frequency varies between f_1 and f_2, the focused fields will be moving between F_1 and F_2. Varying the frequency outside the range between f_1 and f_2, the threshold points can be observed as well, where the focused beam reduces to half of its maximum magnitude.

Figure 40 shows the normalized E-field versus frequency in the y-direction at z_f. It can be observed that at the design frequency f_0, the focused radiated fields are at point F_0. Since F_0 is not a focal point, the maximum E-field does not happen here, but it is very close to the maximum as the dimension of the array and the focal point chosen does not allow the magnitude to reduce much between F_1 and F_2. At the frequency of 2.03 GHz (f_1), the radiated field is focused at F_1 and the magnitude of the fields is maximum at this point. As the frequency is further reduced from 2.03 GHz, the magnitude of the E-field reduces. At the frequency of 1.87 GHz, the focused beam shifts to the point (0, -0.635, 600) mm, where the magnitude of the E-field reduces to 3 dB of its maximum value. The focused beam happens to be at the focal point F_2 when the frequency f_2 is 2.92 GHz. Again, as it is a focal point, the magnitude of the focused field is maximum here, as in the case of F_1. At the frequency of 3.06 GHz, the focused beam moves further in the direction of the positive y-axis to a point (0, 445, 600) mm, where the grating lobes are approximately -10 dB. The total scan distance in positive and negative y-direction is calculated as 1080 mm.

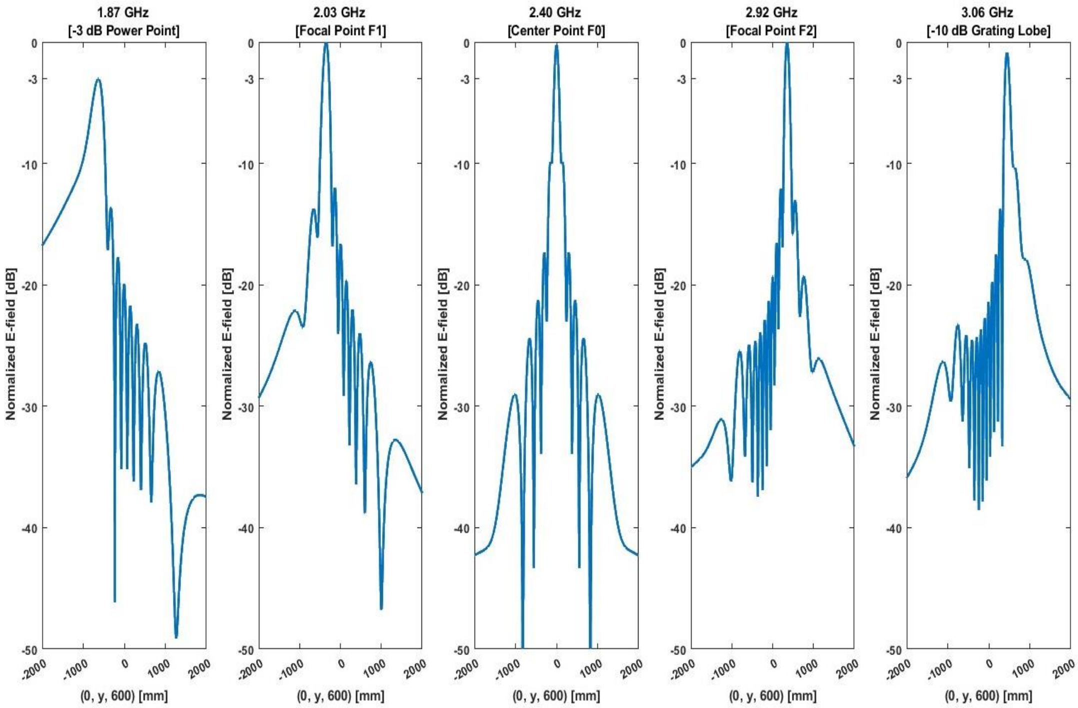

Figure 40: Dual Focal Point 16 × 16 Near-field Focused Antenna Array

By comparing the scan distances from both the single focal point and dual focal point NFF antenna arrays, it can be concluded that the dual focal point antenna array covers more scanning distance as compared to the single focal point. The improvement in the scanning distance is approximately 53%.

It can be observed from the results of both the single focal and dual focal point near-field focused antenna arrays, that as the frequency increases, at a certain point the radiated fields encounter grating lobes before reaching the -3 dB point. The main reason for this behavior is that as the frequency increases, the wavelength decreases and for the focused spot to reach a certain distance it takes more wavelengths as compared to the frequencies below 2.4 GHz. Due to these grating lobes, the scanning distance decreases as the -3 dB point is out of the scanning range.

One way of minimizing this problem is to reduce the inter-element spacing. The inter-element spacing is already very small in this case. The other way is to modify the $(\mathrm{m}-1)\lambda_0$ transmission lines. Previously, the $(\mathrm{m}-1)\lambda_0$ transmission line lengths between two successive level elements were λ_0. If $(\mathrm{m}-1)\lambda_0$ transmission line lengths are replaced by multiples of it, the frequency range for scanning will be reduced greatly and hence the grating lobes will be delayed.

For instance, the 16×16 near-field focused isotropic radiators antenna array for dual focal points discussed in the previous section faces the same issues. The focused field encounters grating lobes at the frequency of 3.06 GHz, although the magnitude of the focused beam is hardly reduced by 1 dB. If the $(\mathrm{m}-1)\lambda_0$ transmission line lengths are replaced by $2(\mathrm{m}-1)\lambda_0$, then two successive level elements would be doubled. The difference between levels m=1 and m=2 would be $2\lambda_0$. The difference between levels m=1 and m=3 would be $4\lambda_0$ and so on.

Figure 41 & 42 shows the normalized E-field versus variation in frequency for 16×16 dual focal point near-field focused antenna array with $2(m-1)\lambda_0$ transmission line lengths for scanning the focused fields. In Figure 41 at the frequency of 2.4 GHz, the focused beam is at the center point F0 (0, 0, 600) mm. As it is not a focal point, the magnitude of the field is not maximum. As the frequency is reduced from 2.4 GHz, the focused field moves in the negative y-direction as expected. At 2.20 GHz the focused fields are at the focal point F_1 (0, -350, 600) mm with the maximum magnitude of the fields. In case of $(\mathrm{m}-1)\lambda_0$ the same point was happening at the frequency of 2.03 GHz. As the frequency is reduced more, at 2.1 GHz, the -3 dB point is encountered at points (0, -635, 600) mm. In case of $(\mathrm{m}-1)\lambda_0$ the same point was happening at the frequency of 1.87 GHz.

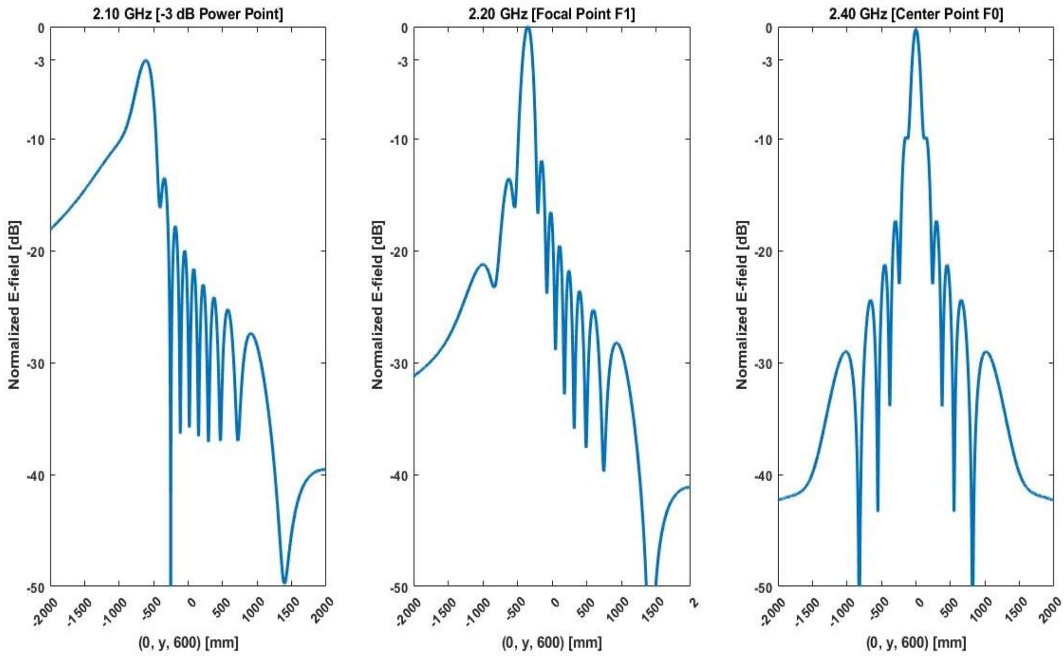

Figure 41: Dual Focal Point 16×16 NFF Antenna Array with Transmission Line Lengths $2(m-1)\lambda_0$

Figure 42 plots normalized E-field versus variation in frequency. As the frequency is increased above 2.4 GHz, the focused fields start moving in the positive y-direction. Focal point F_2 happens to be at point (0, 350, 600) mm when the frequency is 2.63 GHz. In case of $(m-1)\lambda_0$ the same point was happening at the frequency of 2.92 GHz. As the frequency is increased more, the -3 dB point is reached (0, -560, 600) mm at the frequency 2.76 GHz. In case of $(\mathrm{m}-1)\lambda_0$ the same point was happening at the frequency of 3.06 GHz. In $(\mathrm{m}-1)\lambda_0$ case, the -3 dB point was not reached as the grating lobe level was high.

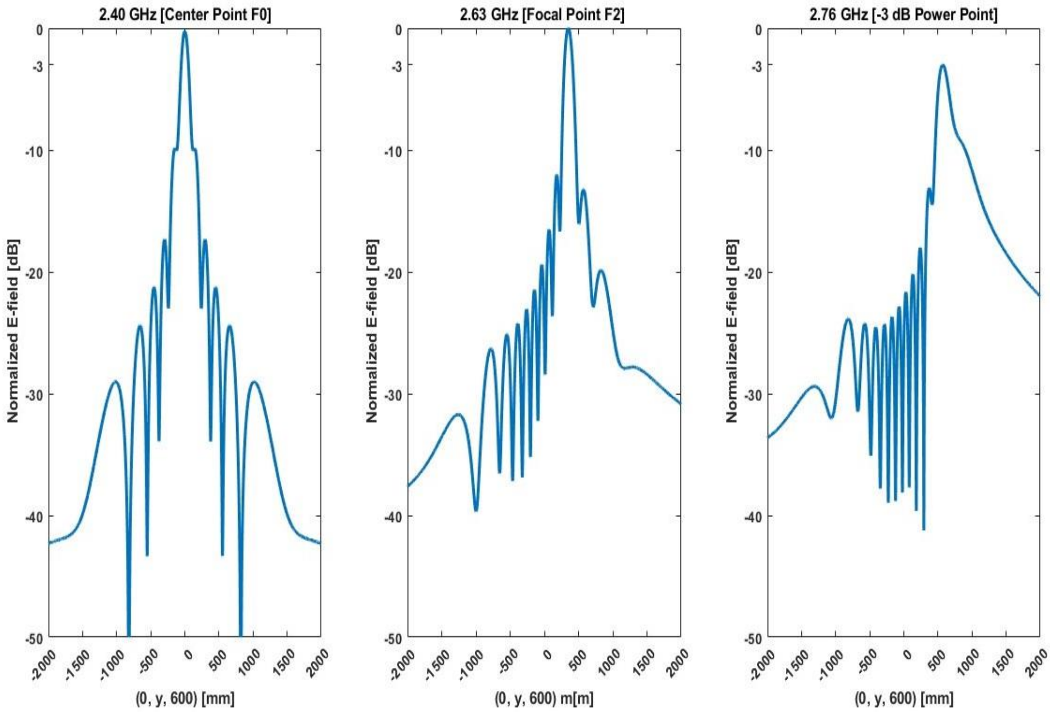

Figure 42: Dual Focal Point 16×16 NFF Antenna Array with Transmission Line Lengths $2(m-1)\lambda_0$

As the -3 dB point can be reached in both directions now, the total scanning distance is improved and it is 1195 mm along the y-direction. It is worth mentioning here that $2(\mathrm{m}-1)\lambda_0$ does not extend the -3 dB points but delays the grating lobes so that the -3 dB point can be reached with a reduced range of frequencies. Furthermore, $(\mathrm{m}-1)\lambda_0$ can be replaced by a general term $\mathrm{T}(\mathrm{m}-1)\lambda_0$. In this case T=2. To reduce the frequency range more, T can be replaced by 3, 4, and so on depending upon the required goal, but with the expanse of too many transmission lines in the structure. In some cases, the antenna array structure might not be big enough to accommodate such long transmission lines.

6.3 Conclusion

In this chapter, a dual focal point NFF 16×16 antenna array has been analyzed to improve the scanning distance. The proposed design uses $w_{n,m}$ and $(\mathrm{m}-1)\lambda_0$ transmission lines as in the previous chapter but for two focal points this time. The simulation results show that at the respective frequency, the radiated fields are focused at the focal points.

Furthermore, the focused beam can be moved as a function of variation in frequency. Comparison has been made between a single focal point and dual focal point antenna arrays with similar parameters. The dual focal point antenna array shows an improvement of approximately 53% in the scanning distance as compared to the single focal point for the chosen example. The proposed design can be used in applications, where the scanning area is large and cannot be scanned using conventional methods.

Chapter 7

CONCLUSION AND FUTURE WORK

7.1 Conclusion

The rapid pace of technological advancements has opened new ways for researchers to work. On one hand, technologies and devices are getting improved but it also brings out more questions to be answered and this is the motivation that leads the researchers to work continuously. Near-field focusing is one of the important applications of antenna arrays, which utilizes the focusing of radiated fields from the antenna arrays into a spot-limited region.

A 4×4 rectangular microstrip patch antenna array is presented in Chapter 4 for focused field enhancements. The array design uses parasitic patch elements to further enhance the radiated field at the focal point. Simulation results show a meaningful improvement in comparison to the conventional NFF antenna array. The proposed design provides a very high level of concentrated fields without any extra input power and can be used in applications where highly focused fields are required. The proposed system not only raises the magnitude of the radiated fields at the focal point but also saves useful power.

A thorough study has been made in Chapter 5 regarding near-field focusing antenna array design, where the focused spot scans the regions of interest by the variation in frequency. For applications where it is necessary to scan a specific region or multiple targets are to be exposed to the focused radiations, the proposed system is efficient and it saves human and machine efforts of the conventional beam scanning mechanisms. A 16×16 antenna array of point radiators gives the basic working principle of beam scanning. The simulation results show that with the variation in frequency, the focused beam can be scanned or moved by approximately 1150 mm in a certain plane.

The idea has been implemented by simulating an 8×8 rectangular patch antenna array using an FR-4 substrate fed by a microstrip feed line. The feed line network has been designed in a way to provide the means for scanning with variation in frequency. The simulations show that the proposed design can scan the focused beam for approximately 310 mm in one plane. The said antenna array design can be used in applications where the region of interest is large enough to be scanned or multiple targets are to be tackled.

A 16×16 antenna array with dual focal points near field focusing has been proposed in Chapter 6. With the combination of quadratic phase distribution and additional wavelength transmission lines, the radiated field can be focused at two points and can be moved in a certain direction as a function of frequency. The proposed antenna array is compared with the single focal point near field focused array and an improvement of approximately 53% has been recorded for the chosen example. This proposed antenna system is highly advantageous in applications where a large region of interest has to be scanned. The mechanism of shifting the focused beam is very accurate and robust and unlike the conventional beam scanning systems, it does not depend on any external phase shifter mechanism or changing the position of the antenna array physically.

7.2 Future Work

7.2.1 Fabrication and Measurement of Single Focal Point Patch Antenna Array

The future work includes the practical implementation of the single focal point patch antenna array discussed in Chapter 5. In Chapter 5, a single focal point 8×8 rectangular microstrip patch antenna was designed in CST simulation software at the frequency of 2.4 GHz. To construct a physical prototype of the said design, the CST file has to be converted to a format that is compatible with the fabrication system. In the first step, the CST file is to be converted to a Gerber (.grb) file. The Gerber file consists of all the details of the antenna array design e.g., the number of layers, the dimensions of each layer, the material of each layer, and parts within the same layer.

In the proposed design, two FR-4 substrates each with a thickness of dielectric 0.8 mm are chosen. One FR-4 substrate will be double-sided copper clad while the other one will be single-sided copper cladded. The thickness of the copper will be 0.035 mm. On the single-sided copper-clad substrate the feed network will be designed using a PCB milling machine. The PCB milling machine is fed with the Gerber file of the design and according to the information in the file, a sharp mill with very high accuracy removes the unwanted copper leaving behind only the feed network. One side of the double-sided copper-clad FR-4 substrate will serve as the ground plane while on the other side, the rectangular microstrip patch antenna array will be milled.

Once both the feed network and the antenna array elements are ready, a drill machine of appropriate size will be used to make holes for the conducting pins. This a very crucial point and the drill needs to be handled very carefully. The holes must be aligned in both substrates to avoid any mismatch. Also, it is very important at this stage to remove the conducting copper from the ground plane around the pin locations preventing short circuits. Once the holes are done, each pin will be inserted and soldered at both ends. The process will continue till all the pins are inserted and soldered. At the end, a 50 Ω SMA connecter will be soldered at the reference excitation point so that the fabricated antenna array systems are connected to different devices using a 50 Ω coaxial cable.

Measuring the characteristics of the prototyped design is a difficult task. For accurate results, the fabricated antenna array has to be tested in the anechoic chamber. An anechoic chamber is a shielded room whose floor, ceiling, and walls are covered with sound or electromagnetic waves absorbing material. Antenna measurements without an anechoic chamber are not accurate as they include the reflection of electromagnetic waves from nearby surfaces. The very first and most important parameter of the antenna array that will be measured is the S-parameter. The S-parameter is the measure of the amount of reflection coming back into the antenna array system. For a perfectly impedance-matched antenna array, there will be no reflections coming back. A Network Analyzer is a device that can measure the S-parameter. A 50 Ω output coaxial cable of the network analyzer is connected to the antenna array system and the S-parameter of the antenna arrays can be calculated at a range of frequency.

Once the S-parameter is satisfactory, the antenna array needs to be set in the anechoic chamber to measure the other required parameters. In this case, the aim is to measure the power density or E-field at the focal point as well as along the scanning axis i.e., in the y-direction. A typical anechoic chamber has two towers, the transmitting antenna tower and the receiving antenna tower, where the antennas are mounted. The transmitting antenna mounted on the transmitting antenna tower is excited by an excitation source while the receiving antenna's output is connected to measuring devices such as a power meter or antenna radiation pattern measurement devices. Figure 43 illustrates an anechoic chamber with transmitting and receiving antennas mounted on the stands.

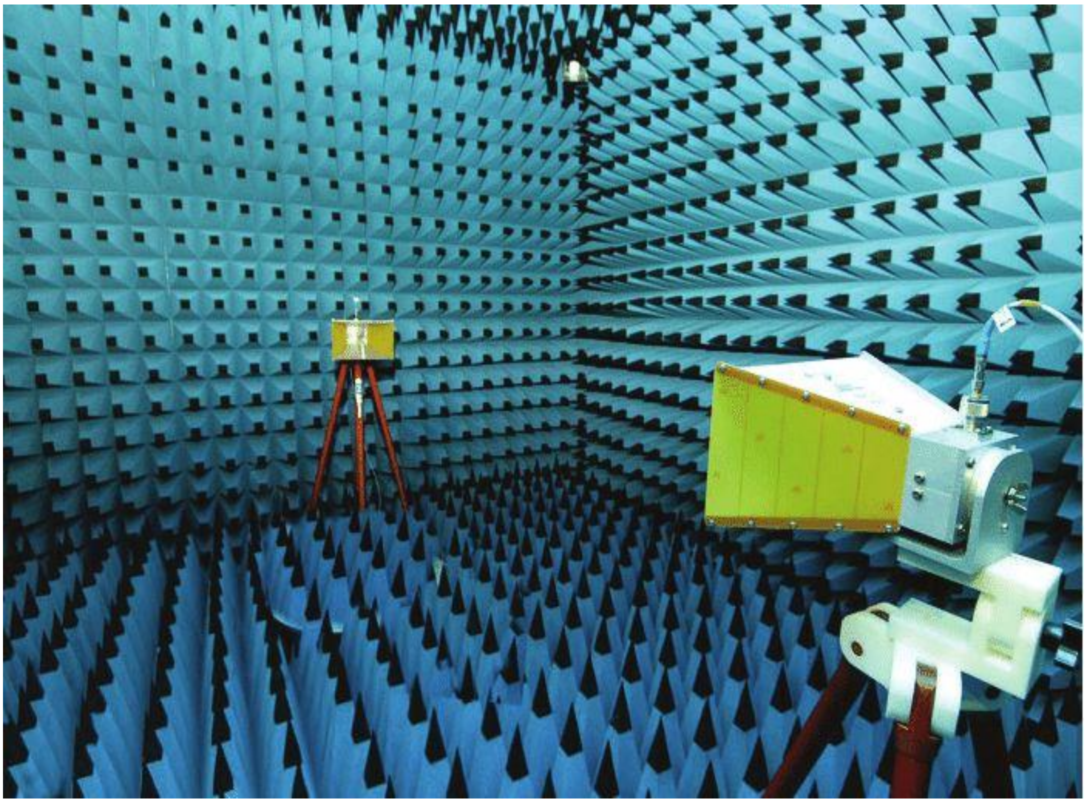

Figure 43: An Anechoic Chamber[43]

The fabricated 8×8 single focal point patch antenna array serves here as a transmitting antenna connected to an excitation source, while a receiving antenna will be mounted at the other tower to measure the radiated fields from the transmitting antenna array. The receiving antenna must be connected in such a way that the position of the antenna in the vertical direction (y-axis/scanning axis) can be changed (adjusted). Figure 44 shows, the antenna measurement setup for the fabricated patch antenna array.

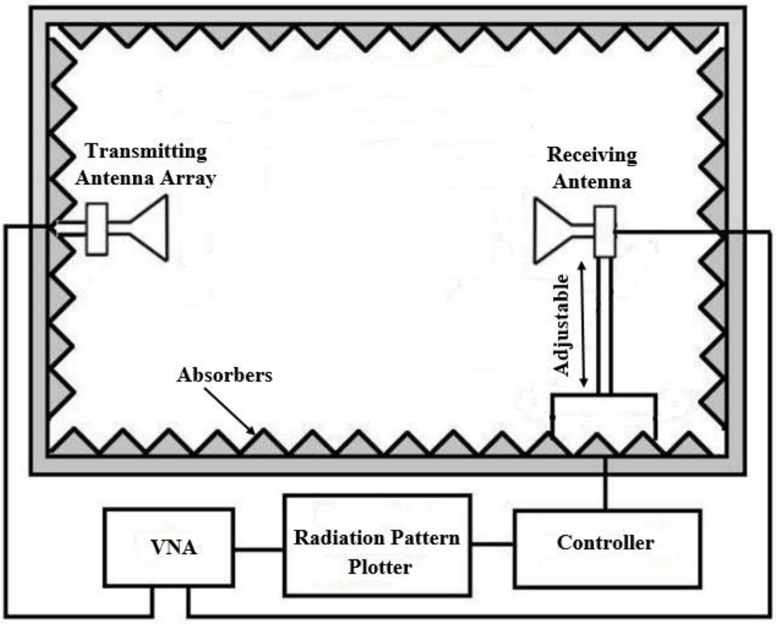

Figure 44: Antenna Array Measurement Setup

In the beginning, the receiving antenna is kept at the focal point and the measurements are done. Iteratively, the receiving antenna position is changed vertically (y-direction) and in each iteration, the measurements are done for a certain frequency. The process can be automated so that linear radiation patterns can be plotted by a plotter. In this way, the whole fabrication and measurement process is proposed.

7.2.2 CST Simulations, Fabrication, and Measurement of Dual Focal Point Patch Antenna Array

To validate the Matlab simulations done in Chapter 6, the dual focal point near-field focused patch antenna will be designed and analyzed in CST Studio Suite. The basic idea of the design is the same as the single focal point near-field focused patch antenna array except for the positions of the individual elements and the transmission line lengths fed to each element.

Once the antenna array is designed and compared with the Matlab simulations, the said CST antenna array design will be fabricated and presented for measurements. The fabrication and measurement will be carried out, in the same way, explained in the previous section, as both the single and dual focal point antenna arrays are based on the same principle and have the same scanning axis. The final checkpoint would be tallying the results from both the simulations and measurements.

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