Circularly Polarized Microstrip Antenna

Marwa Shakeeb

A Thesis

In

The Department

of

Electrical and Computer Engineering

Concordia University

Presented in Partial Fulfillment of the Requirements
for the Degree of Master of Applied Science (Electrical Engineering) at
Concordia University
Montreal, Quebec, Canada

December 2010

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

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By: Marwa Shakeeb

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Master of Applied Science

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Signed by the final examining committee:

______________________________ Chair
Dr. D. Qiu

______________________________ Examiner, External To the Program
Dr. A. Ben Hamza, CIISE

______________________________ Examiner
Dr. T. Denidni

______________________________ Supervisor
Dr. A. Sebak

Approved by: ______________________________
Dr. W. E. Lynch, Chair
Department of Electrical and Computer Engineering

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Dr. Robin A. L. Drew
Dean, Faculty of Engineering and Computer Science

Abstract

Circularly Polarized Microstrip Antenna

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Matching the polarization in both the transmitter and receiver antennas is important in terms of decreasing transmission losses. The use of circularly polarized antennas presents an attractive solution to achieve this polarization match which allows for more flexibility in the angle between transmitting and receiving antennas, reduces the effect of multipath reflections, enhances weather penetration and allows for the mobility of both the transmitter and the receiver.

The objective of this thesis is to design a single fed circularly polarized microstrip antenna that operates at 2.4 GHz. Single feeding is used because it is simple, easy to manufacture, low in cost and compact in structure. This thesis presents a new design for a circularly polarized antenna based on a circular microstrip patch. Circular polarization is generated by truncating two opposite edges from a circular patch antenna at 45° to the feed. The truncation splits the field into two orthogonal modes with equal magnitude and 90° phase shift. The perturbation dimensions are then optimized to achieve the low axial ratio required to achieve circular polarization at the desired frequency. This thesis presents three design variations. The first design is fed by microstrip line feed, the second is fed by proximity feeding and the third is fed by aperture feeding. The design of the microstrip fed antenna requires parametric studies on the antenna diameter and the distance between the patch center and the truncation. It also required designing a quarter

wavelength transformer between the 50 Ω feed line and the patch. The design of the proximity fed antenna requires one additional parametric study on the length of the feed line while the aperture fed antenna requires two additional parametric studies on the length of the feed line and the diameter of the ground slot.

Results show that microstrip fed antenna design in this thesis can yield 8.11 dB directive gain, axial ratio and impedance bandwidth 0.83 % and 2.92 % respectively. The proximity fed antenna in this thesis can yield 8 dB directive gain, axial ratio and impedance bandwidth 1.45 % and 5.36 % respectively. The aperture fed antenna in this thesis can yield 7.92 dB directive gain, axial ratio and impedance bandwidth 0.83 % and 2.92 % respectively.

To Mohamed, Hana and Karim

Acknowledgement

I would like to express my deepest appreciation and gratitude to my academic and research advisor, Professor A. Sebak for his advice and invaluable guidance throughout my research. This work would have been impossible without his precious support and encouragement.

I would like to thank the members of my examining committee Dr. Abedesamad Ben Hamza, Dr. Dongyu Qiu and Dr. Tayeb A. Denidni. I especially want to thank my colleague Dr. Michael Wong for his help and support whenever needed. I would like to thank Dr. Hany Hammad Associate Professor at GUC for his help and cooperation.

My deepest gratefulness goes to my husband Mohamed Ashour for his love, help and support during my studies. I'm really lucky couldn't have made it without him. Special thanks to the wonderful mother I'm blessed with; Khadiga for her endless extraordinary support in every aspect in my life. Last but not least I would like to thank my daughter Hana and my son Karim for giving me the time to finish my studies.

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L	Patch length,
W	Patch width,
W_f	50Ω feed line width
L_f	50Ω feed line length
L_{tr}	Quarter wave length transformer length
W_{tr}	Quarter wave length transformer Width
l	Inset Depth
$\mathcal{w}$	Inset separation from patch
W_g	Air gap width
h	Dielectric substrate height
rad	circular patch radius
rad_{slot}	circular slot radius

f_r Design frequency

f_c Center frequency

λ_o Free space wave length

λ_{eff} Effective wavelength

$\mathcal{E}_r$ Substrate dielectric constant

$\mathcal{E}_{eff}$ Effective substrate dielectric constant

n Integer

$\Delta\varphi$ time difference between electric field components

ξ Instantaneous electric field intensity

E Maximum electric field magnitude

τ Tilt angle

OA polarization ellipse major axis

OB polarization ellipse minor axis

List of Abbreviations

WLAN	Wireless Local Area Network
GPS	Global Positioning System
RFID	Radio Frequency Identification tags
CW	Clock wise
CCW	Counter clock wise
RHCP	Right hand circular polarization
LHCP	Left hand circular polarization

Chapter 1

Introduction

In a typical wireless communication system increasing the gain of antennas used for transmission increases the wireless coverage range, decreases errors, increases achievable bit rates and decreases the battery consumption of wireless communication devices. One of the main factors in increasing this gain is matching the polarization of the transmitting and receiving antenna. To achieve this polarization matching the transmitter and the receiver should have the same axial ratio, spatial orientation and the same sense of polarization. In mobile and portable wireless application where wireless devices frequently change their location and orientation it is nearly impossible to constantly match the spatial orientation of the devices. Circularly polarized antennas could be matched in wide range of orientations because the radiated waves oscillate in a circle that is perpendicular to the direction of propagation [1-3].

The microstrip antenna is one of the most commonly used antennas in applications that require circular polarization. This thesis is concerned with the design of a circularly polarized microstrip antenna that would operate in the 2.4 GHz range. This range is commonly used by wireless local area devices and wireless personal area devices such as the 802.11 WIFI and the 802.15.4 Zigbee wireless systems.

1.1 Motivation

Designing a circularly polarized microstrip antenna is challenging; it requires combination of design steps. The first step involves designing an antenna to operate at a given frequency. In the second step circular polarization is achieved by either introducing a perturbation segment to a basic single fed microstrip antenna, or by feeding the antenna with dual feeds equal in magnitude but having 90° physical phase shift. The shape and the dimensions of the perturbation have to be optimized to ensure that the antenna achieves an axial ratio that is below 3 dB at the desired design frequency.

This thesis achieves circular polarization by introducing a perturbation in the form of truncating two opposite edges of a basic circular patch antenna. Truncated edges have been used to achieve circular polarization in square, elliptical and circular patch in [4-6]. The work in [6] used a coaxial feed and did not provide details about the parametric optimization of this antenna. Coaxial feed is not suitable for array since a large number of solder joints will be needed and high soldering precision.

Single feeding techniques are commonly used because they are simple, easy to manufacture, low in cost and compact in structure. Single fed circularly polarized microstrip antennas are considered to be one of the simplest antennas that can produce circular polarization [7]. In order to achieve circular polarization using only a single feed, two modes should be exited with equal amplitude and 90° out of phase. Since basic microstrip antenna shapes produce linear polarization there must be some deviation in the patch design to produce circular polarization. Perturbation segments are used to split the field into two orthogonal modes with equal magnitude and 90° phase shift. Therefore the circular polarization requirements are met.

1.2 Objective

The objective of this thesis is to present a new circularly polarized single fed microstrip antenna. To obtain this new antenna design a study is performed to compare the effect of different single feeding techniques on the circularly polarized microstrip antenna radiation characteristics.

1.3 Thesis organization

Chapter 2 reviews circularly polarized microstrip antennas. It discusses what a microstrip antenna consists of, methods of analysis, advantages and disadvantages. It also discusses polarization types, feeding of microstrip antenna to generate circular polarization. The chapter also discusses different techniques to generate circularly polarized microstrip antenna with single feed. Among these techniques using square patch antenna with shaped slot, embedding cross slot in the radiating patch, stacking antenna and truncated edges patch.

The presented antenna is based on a circular patch antenna. Two opposite edges from the circular patch were truncated to produce circular polarization. The antenna design methodology and the design of the three proposed antennas are presented in Chapter 3.

Chapter 4 presents design verification for the 3 designed antennas using CST software and measured prototype. It also discusses the HFSS simulation results of the 3 antennas.

The microstrip fed antenna was manufactured and tested. The measured results are compared with the simulated using HFSS and CST.

It also presents a comparison between the 3 antennas dimensions and radiation output.

Finally the conclusion and future work are presented in Chapter 5.

Chapter 2

Circularly polarized microstrip patch antenna

The idea of microstrip antenna was first founded by Deschamps in 1953 [8]. It was patented in 1955 [9] but the first antenna was fabricated during the 1970's when good substrates became available. Since then, microstrip antennas continuously developed to become one of the most attractive antenna options in a wide range of modern microwave systems. This fast growth in microstrip antenna applications and uses derived a continuous research effort for developing and improving its characteristics [10-11].

In a typical communication system, increasing the gain of antennas used for transmission and reception play a major role in enhancing the system performance. One of the main factors in increasing this gain is matching the polarization of the transmitting and receiving antenna. Polarization describes the orientation of oscillations in the plane perpendicular to a transverse wave's direction of travel. These wave planes could linearly oscillate in the same direction or their direction and amplitude could change such to follow an elliptical contour. Polarization matching reduces the transmission loss by aligning the orientation of these wave propagations in both the transmitting and receiving antennas. To achieve this matching the transmitter and the receiver should have the same axial ratio, spatial orientation and the same sense of polarization. Achieving this match is challenging in wireless technologies that require mobility and portability such as WLAN, GPS and RFID. The use of circularly polarized antennas presents an attractive solution to achieve this polarization match. When receiving a circularly polarized wave, the antenna orientation is not important to be in the direction perpendicular to the propagation direction, hence allowing for more portability.

Microstrip antenna is one of the most popular antennas used for the production of circular polarization. Microstrip antennas on their own do not generate circular polarization. Circular polarization is achieved in microstrip antenna by either introducing a perturbation segment to a basic single fed microstrip antenna, or by feeding the antenna with dual feed equal in magnitude but having 90° physical phase shift. In this thesis we focus on achieving polarization through the introduction of a perturbation to a basic circular microstrip patch. This chapter presents a background about microstrip antennas, circular polarization and feeding techniques to generate circular polarization.

2.1 Advantages and disadvantages of microstrip antennas

The microstrip antenna has several advantages. It is a low profile antenna that can conform to planar and nonplanar surfaces which fits the shape design and needs of modern communication equipment. The microstrip antenna shape flexibility enables mounting them on a rigid surface which makes them mechanically robust. Microstrip antennas can be mass produced using simple and inexpensive modern printed circuit board technologies. The use of printed circuit board manufacturing technologies also enables fabricating the feeding and matching networks with the antenna structure. It can also be integrated with MMIC designs. From a designer point of view microstrip antenna presents a wide range of options. The designer can vary the choice of the substrate type, the antenna structure, type of perturbation and the feeding technique to achieve the antenna design objective [11-13].

Microstrip antennas have a narrow impedance bandwidth, low efficiency and they can only be used in low power applications. When used in scanning applications, microstrip antennas show a poor performance. They also show high ohmic losses when used in an array structure. Polarization polarity given by microstrip antenna is poor. Most microstrip antennas radiate only in half-space, because they are implemented on double sided laminates where one side is used as a ground. The half space radiation limits their use in some application. The research in microstrip antenna design mainly focuses on how to overcome these disadvantages [11-13].

2.2 Microstrip antenna

Microstrip antenna in its basic form consists of 4 parts (metallic patch, dielectric substrate, ground plane and feeding structure) as shown in Figure 2-1. Where L is the length of the patch, W is the width of the patch, h is the dielectric substrate height and ε_r substrate relative permittivity.

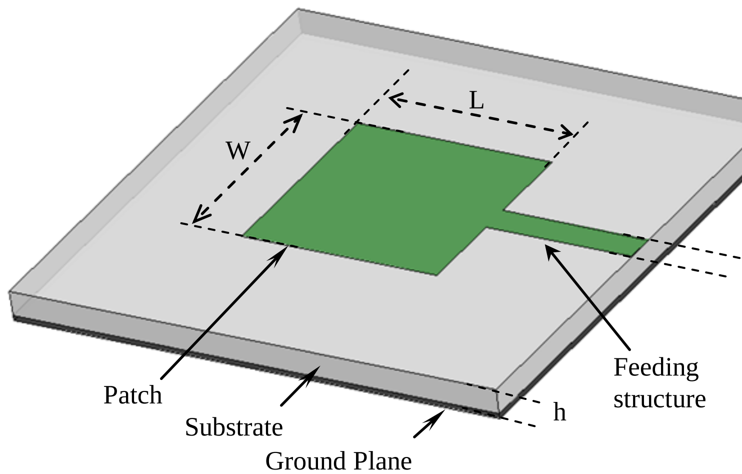


Figure 2-1: Basic Microstrip antenna

2.2.1 Metallic patch

It consists of a very thin metallic sheet mounted on dielectric substrate. The antenna patch shape as shown in Figure 2-2 can be square, rectangular, strip, circular, triangular, elliptical, or any combination of these shapes. Every shape has its own characteristics and is chosen to meet certain requirements. The square, rectangular, and circular are the most popular shapes because they are the easiest in analysis and fabrication.

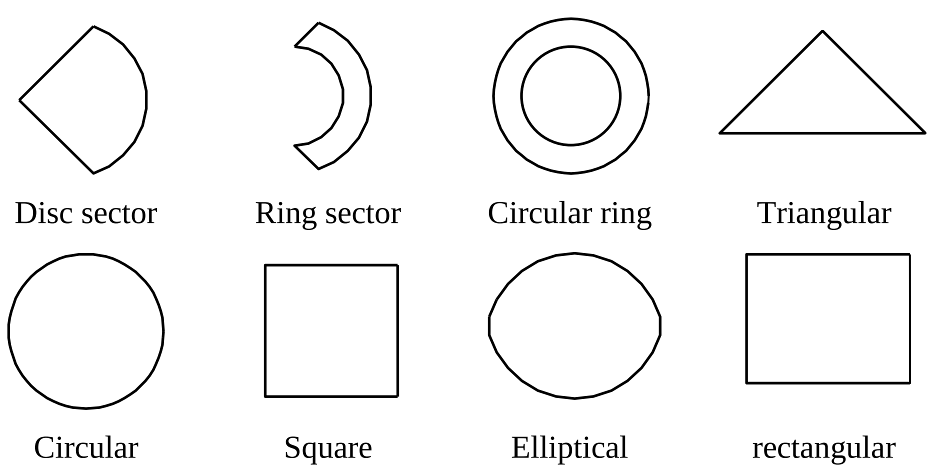


Figure 2-2 Different shapes for microstrip antenna

2.2.2 Dielectric substrate

It is the dielectric layer between the patch and the ground. There are a lot of substrate material and specifications to choose from according to the antenna requirement. The most two factors specifying dielectric substrate is substrate height ($0.003\ \lambda_o \leq h \geq\ 0.05\ \lambda_o$) and dielectric constant ($2.2 \leq \mathcal{E}_r \leq 12$). As $\mathcal{E}_r$ gets higher in value the antenna size gets smaller.

Substrates that are thick with low dielectric constant are preferable for enhancing efficiency, bandwidth and radiation in space. On the other hand substrates that are thin with high dielectric constant are preferable for microwave circuits.

2.2.3 The ground

It is the metallic part found on the other side of the substrate. There are some perturbations that can be done to the ground to enhance the antenna performance towards certain specifications, like inserting shapes or slots in the ground plane [11, 14-15].

2.2.4 Feeding

The most four popular feeding techniques for microstrip patch antenna are: (coaxial feeding, microstrip feeding, proximity feeding and aperture feeding).

2.2.4.1 Coaxial feeding

It is one of the basic techniques used in feeding microwave power. The coaxial cable is connected to the antenna such that its outer conductor is attached to the ground plane while the inner conductor is soldered to the metal patch [1, 11-12].

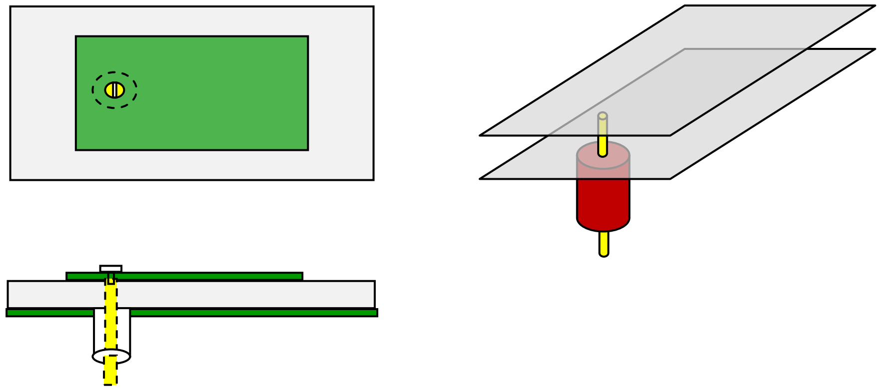


Figure 2-3 Coaxial feeding

Coaxial feeding is simple to design, easy to fabricate, easy to match and have low spurious radiation [11-12]. However coaxial feeding has the disadvantages of requiring high soldering precision. There is difficulty in using coaxial feeding with an array since a large number of solder joints will be needed. Coaxial feeding usually gives narrow bandwidth and when a thick substrate is used a longer probe will be needed which increases the surface power and feed inductance [11-13].

2.2.4.2 Microstrip feeding

In microstrip feed, the patch is fed by a microstrip line that is located on the same plane as the patch. In this case both the feeding and the patch form one structure. Microstrip feeding is simple to model, easy to match and easy to fabricate. It is also a good choice for use in antenna-array feeding networks. However microstrip feed has the disadvantage of narrow bandwidth and the introduction of coupling between the feeding line and the patch which leads to spurious radiation and the required matching between the microstrip patch and the 50 Ω feeding line. Microstrip feed can be classified into 3 categories:

Direct feed: where the feeding point is on one edge of the patch. As shown in Figure 2-4. Direct feed needs a matching network between the feed line and the patch (such as quarter wavelength transformer). The Quarter wave length transformer compensates the impedance differences between the patch and the 50 *Ω* feed line. The quarter wave length transformer is calculated according to formulas found in [12, 16].

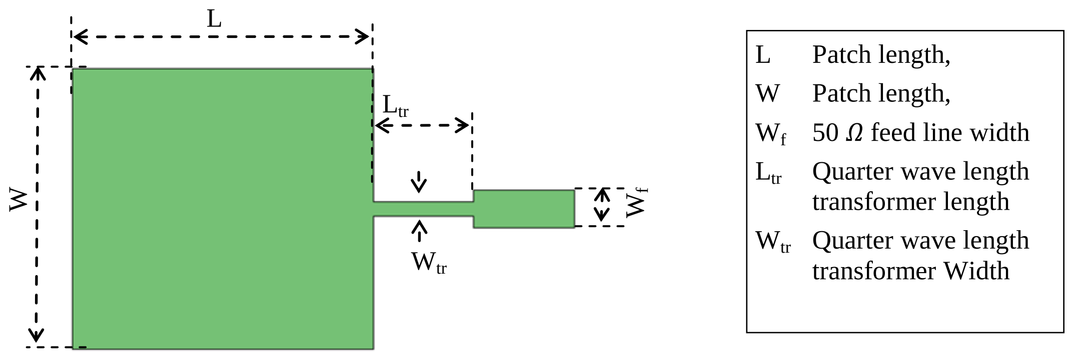


Figure 2-4 Direct microstrip feed line

Inset feed**:** where the feeding point is inside the patch. The location of the feed is the same that will be used for coaxial feed. The 50 *Ω* feed line is surrounded with an air gap till the feeding point as shown in Figure 2-5 . The inset microstrip feeding technique is more suitable for arrays feeding networks [11-13].

Gap-coupled*:* the feeding line does not contact the patch; there is an air gap between the 50 *Ω* line and the patch as shown in Figure 2-6 .The antenna is fed by coupling between the 50 *Ω* feed line and the patch.

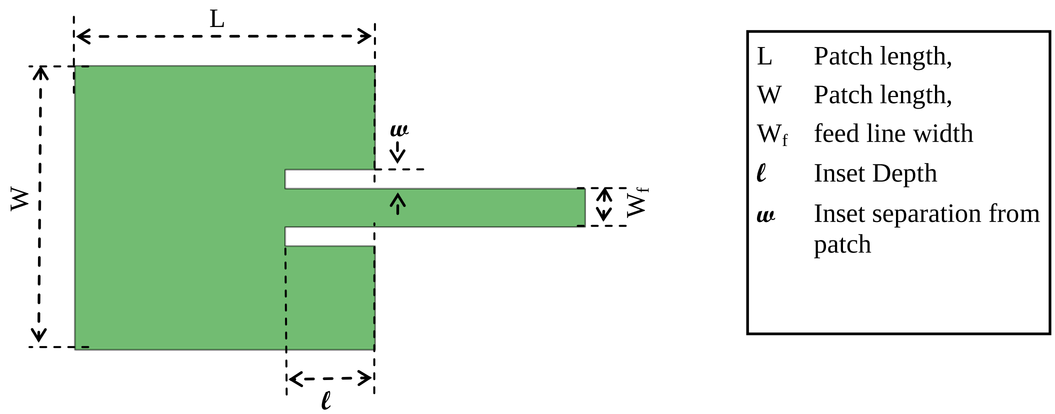


Figure 2-5 Inset microstrip feed line

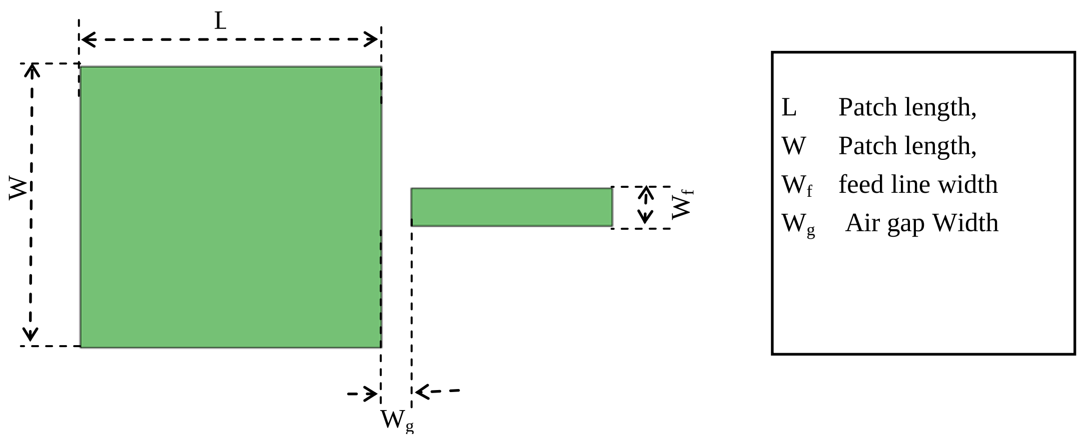


Figure 2-6 Gap-coupled microstrip feed line

2.2.4.3 Proximity coupled feeding

Proximity coupled feeding consists of two dielectric substrate layers. The microstrip patch antenna is located on the top of the upper substrate & the microstrip feeding line is located on the top of the lower substrate as shown in Figure 2-7. It is a non contacting feed where the feeding is conducted through electromagnetic coupling that takes place between the patch and the microstrip line. The two substrates parameters can be chosen different than each other to enhance antenna performance [11, 13]. The proximity coupled feeding reduces spurious radiation and increase bandwidth. However it needs precise alignment between the 2 layers in multilayer fabrication.

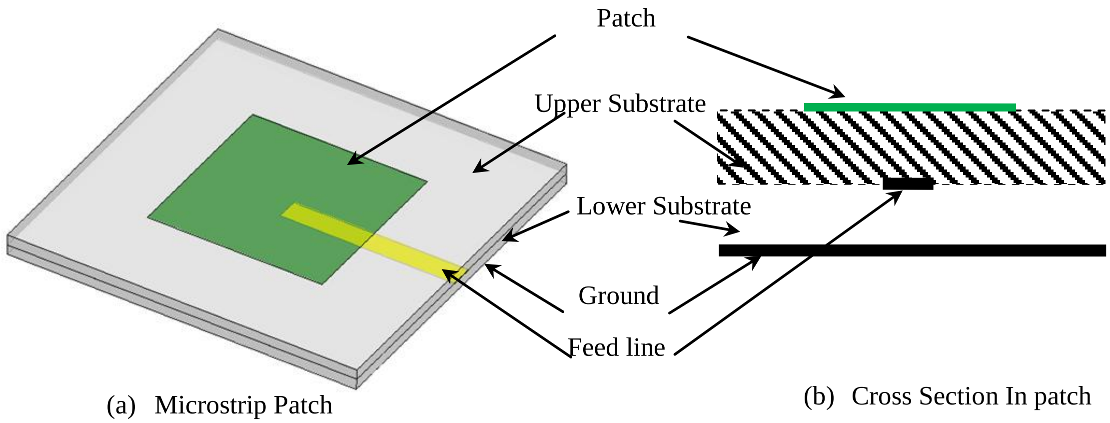


Figure 2-7 Proximity coupled microstrip feeding

2.2.4.4 Aperture – coupled feeding

Aperture coupled feeding consists of two substrate layers with common ground plane in-between the two substrates , the microstrip patch antenna is on the top of the upper substrate & the microstrip feeding line on the bottom of the lower substrate and there is a slot cut in the ground plane as shown in Figure 2-8. The slot can be of any size or shape and is used to enhance the antenna parameters. It is a non contacting feed; the feeding is done through electromagnetic coupling between the patch and the microstrip line through the slot in the ground plane. The two substrates parameters can be chosen different than each other to enhance antenna performance [1-2, 11-13]. The aperture feeding reduces spurious radiation. It also increases the antenna bandwidth, improves polarization purity and reduces cross-polarization. But it has the same difficulty of the aperture feeding which is the multilayer fabrication.

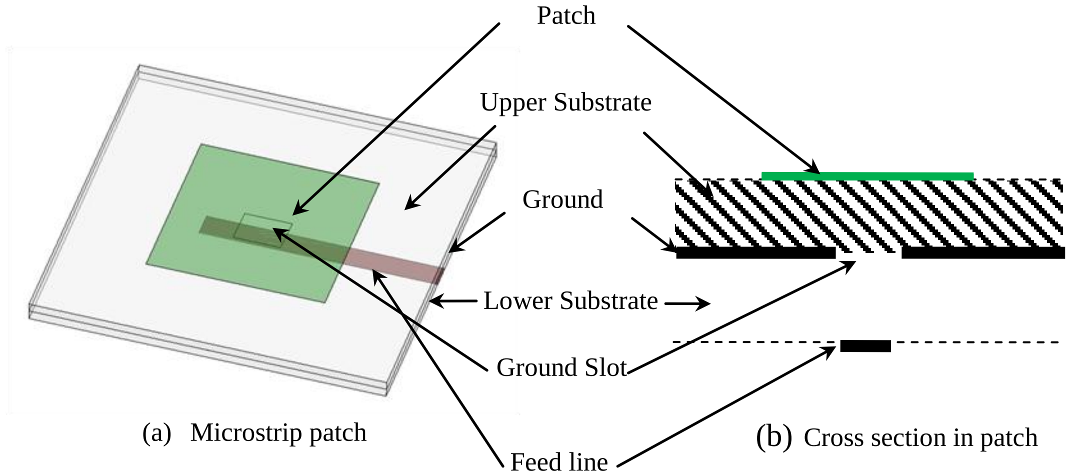


Figure 2-8 Aperture coupled microstrip feed

2.2.5 Methods of analysis

Due to the attention given to the microstrip antenna and the importance to understand its physical insight there are many methods to analyze microstrip antennas. Among these methods, ***Transmission-line model***: it is the simplest and easiest model. It gives good physical insight. However it is not versatile, less accurate and difficult in modeling coupling [11, 13]. ***Cavity model***: it is more complex than the transmission-line model and also difficult in modeling coupling. However it is more accurate and gives more physical insight [11, 13]. ***Full wave***: it is the most accurate and versatile model, it can be applied to any microstrip antenna structure. However it is very complex and gives less physical insight [11, 13].

Microstrip antennas drawbacks are sometimes beneficial. There are some applications that require narrow frequency bandwidth such as government security systems. There are many modifications techniques that can be done to overcome some of the microstrip antenna disadvantages. Stacking, choosing thick substrate, coplanar parasitic elements can increase the antenna bandwidth up to 60% or more. Array configuration can be used to overcome low gain and low power. Photonic bandgap structures can be used to overcome poor efficiency, mutual coupling, reduced gain and radiation pattern degradation [11].

Due to the advantages and ease of fabrication of Microstrip antenna it is the most antenna elements that has a variety in its designs [10]. There are a lot of antenna combinations based on: patch shape, feeding technique, substrate parameters, perturbations technique if used and array arrangements, the combination of these parameters can be optimized to meet a wide array of antenna requirements.

2.3 Polarization

When a wave is travelling in space the property that describes its electric field rotation at a fixed point as a function of time is called wave polarization. It is a parameter which remains constant over the antenna main beam but may vary in the minor loops. Since the electric and magnetic field vectors are always related according to Maxwell's equation, it is enough to specify the polarization of one of them. And generally it is specified by the electric field [1, 17-18]. Polarization should be defined in its transmitting mode with reference to IEEE Standards [3, 12, 19]. The polarization plane is the plane containing the electric and magnetic field vectors and it is always perpendicular to the plane of propagation [1, 20]. The contour drawn by the tip of the electric field vector describes the wave polarization. This contour is an ellipse, circle or a line [1]. The polarization direction is assumed in the direction of the main beam unless otherwise stated [12].

There are 2 kinds of polarization co-and cross-polarizations. Co-polarization is the polarization radiated/received by the antenna, while the cross-polarization is perpendicular to it [12].

Polarization is a very important factor in wave propagation between the transmitting and receiver antennas. Having the same kind of polarization and sense is important so that the receiving antenna can extract the signal from the transmitted wave [21]. Maximum power transfer will take place when the receiving antenna has the same direction, axial ratio, spatial orientation and the same sense of polarization as incident wave, otherwise there will be polarization mismatch. If polarization mismatch occurs it will add more losses [1-3, 12]. Polarization is very important when considering wave reflection [17].

2.3.1 Types of polarization

The shape of the contour drawn by the tip of the electric field vector is called the polarization ellipse. This ellipse describes everything in polarization as shown in Figure 2-9.

Axial ratio states the shape of the polarization ellipse. *Tilt angle* states its orientation. *The direction* of the electric field vector is the sense of polarization in the direction of propagation [1].

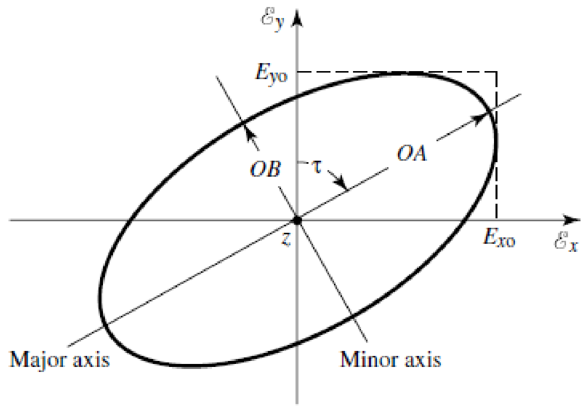


Figure 2-9 Plane wave and its polarization ellipse @Z = 0 [12]

There are three types of polarization (Elliptical polarization, linear polarization and circular polarization) shown in Figure 2-10

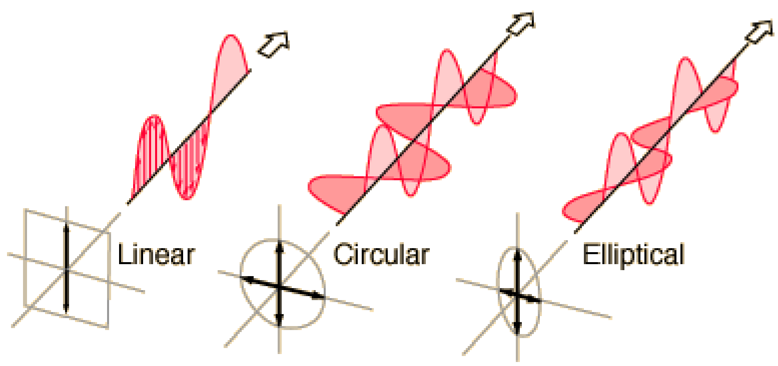


Figure 2-10 Types of polarization

Elliptical polarization is the general polarization state. When the tip of the electric field vector traces an ellipse at a fixed point in space, then it is elliptically polarized. And this happens when the electric field x and y components don't have the same magnitude and the phase difference between them is odd multiples of $\frac{\pi}{2}$.

$$|\xi_x| \neq |\xi_y| \Rightarrow E_x \neq E_y \tag{2.1}$$

$$\Delta\varphi = \varphi_y - \varphi_x = \begin{Bmatrix} +\left(\frac{1}{2}+2n\right)\pi, n = 0,1,2,\ldots\text{.for CW} \\ -\left(\frac{1}{2}+2n\right)\pi, n = 0,1,2,\ldots\text{.for CCW} \end{Bmatrix} \tag{2.2}$$

Or the phase difference between the electric field x and y components is not multiples of

$\frac{\pi}{2}$

$$\Delta\varphi = \varphi_y - \varphi_x \neq \pm\frac{n}{2}\pi = \begin{Bmatrix} > 0, n = 0,1,2,\ldots\text{.for CW} \\ < 0, n = 0,1,2,\ldots\text{.for CCW} \end{Bmatrix} \tag{2.3}$$

where CW is clockwise and CCW is counter clockwise.

The sense of polarization of the elliptical polarization depends on the direction of rotation of the electric field vector, it is determined from the phase leading component to the phase lagging component in a direction away from the observer. If the electric field vector rotates clockwise, it is right-hand elliptical polarization and if the electric field vector rotates counter clockwise; it is left-hand elliptical polarization [12].

When the tip of the electric field vector moves along a line in space, then it is linearly polarized. And this happens when the electric field has only one component or

$$\Delta\varphi = \varphi_y - \varphi_x = n\pi n = 0,1,2,\ldots \tag{2.4}$$

When the tip of the electric field vector traces a circle at a fixed point in space, then it is circularly polarized. And this happens when the electric field x and y components have the same magnitude and the phase difference between them is odd multiples of $\frac{\pi}{2}$.

$$|\xi_x| = |\xi_y| \Rightarrow E_x = E_y \tag{2.5}$$

$$\Delta\varphi = \varphi_y - \varphi_x = \begin{Bmatrix} +(\frac{1}{2} + 2n)\pi, n = 0,1,2,\ldots\text{.for CW} \\ -(\frac{1}{2} + 2n)\pi, n = 0,1,2,\ldots\text{.for CCW} \end{Bmatrix} \tag{2.6}$$

The sense of polarization of the circular polarization depends on the direction of rotation of the electric field vector from the phase leading component to the phase lagging component in a direction away from the observer. If the electric field vector rotates clockwise, it is right-hand circular polarization and if the electric field vector rotates counter clockwise, it is left-hand circular polarization [12].

2.4 Circular polarization and microstrip antenna

Nowadays circular polarization is very important in the antenna design industry, it eliminates the importance of antenna orientation in the plane perpendicular to the propagation direction, it gives much more flexibility to the angle between transmitting & receiving antennas, also it enhances weather penetration and mobility [17, 22]. It is used in a bunch of commercial and militarily applications. However it is difficult to build good circularly polarized antenna [2]. For circular polarization to be generated in microstrip antenna two modes equal in magnitude and 90 out of phase are required [23-24]. Microstrip antenna on its own doesn't generate circular polarization; subsequently some changes should be done to the patch antenna to be able to generate the circular polarization [25]. The circular microstrip patch antenna's lowest mode is the TM_{11}, the next higher order mode is the TM_{21} which can be driven to produce circularly polarized radiation Circularly polarized microstrip antennas can be classified according to the number of feeding points required to produce circularly polarized waves. The most commonly used feeding techniques in circular polarization generation are dual feed and single feed [24].

2.4.1 Dual feed circularly polarized microstrip antenna

As 90° phase shift between the fields in the microstrip antenna is a perquisite for having circular polarization, dual feed is an easy way to generate circular polarization in microstrip antenna. The two feed points are chosen perpendicular to each other as shown in Figure 2-11. With the help of external polarizer the microstrip patch antenna is fed by equal in magnitude and orthogonal feed. Dual feed can be carried out using quadrature hybrid, ring hybrid, Wilkinson power divider, T-junction power splitter or two coaxial feeds with physical phase shift 90° [26-17].

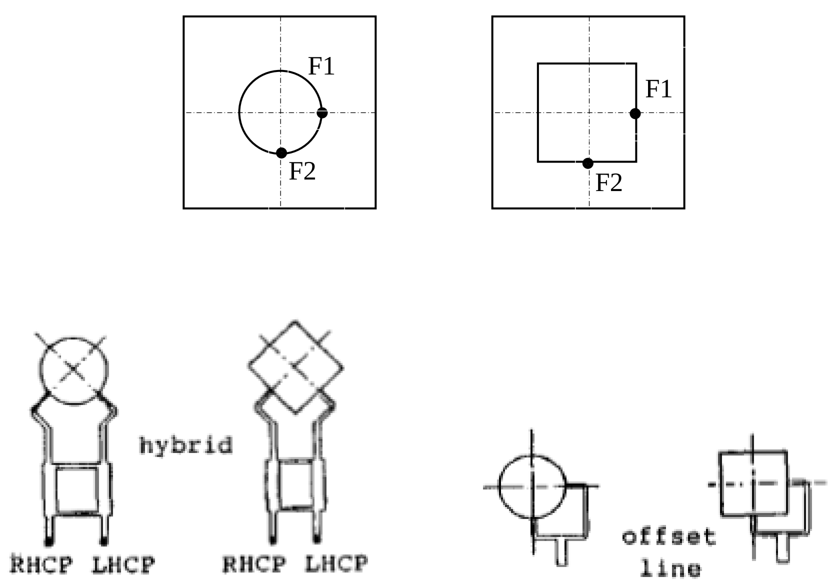


Figure 2-11 Examples for dual fed CP patches [24]

2.4.2 Single feed circularly polarized microstrip antenna

Single fed microstrip antennas are simple, easy to manufacture, low cost and compact in structure as shown in Figure 2-12. It eliminates the use of complex hybrid polarizer, which is very complicated to be used in antenna array [24, 28]. Single fed circularly polarized microstrip antennas are considered to be one of the simplest antennas that can produce circular polarization [7]. In order to achieve circular polarization using only single feed two degenerate modes should be exited with equal amplitude and 90° difference. Since basic shapes microstrip antenna produce linear polarization there must be some changes in the patch design to produce circular polarization. Perturbation segments are used to split the field into two orthogonal modes with equal magnitude and 90° phase shift. Therefore the circular polarization requirements are met.

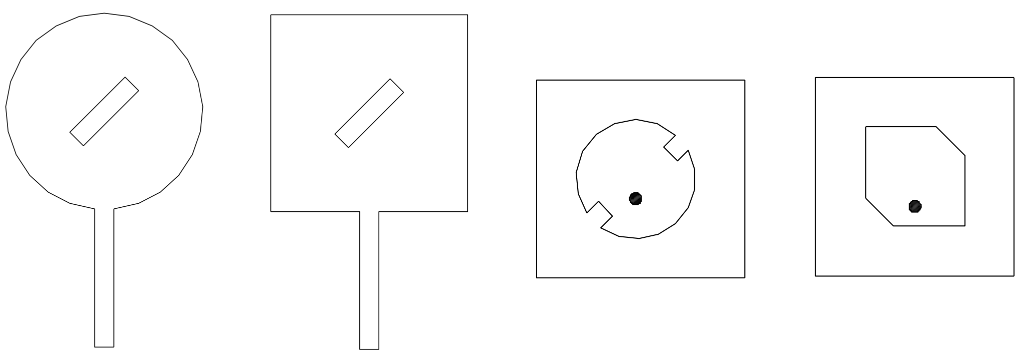


Figure 2-12 single fed patches

The dimensions of the perturbation segments should be tuned until it reach an optimum value at the design frequency [24, 27, 29-30].

Single feeding techniques previously discussed in section 2.1.4.

2.5 Single fed circularly polarized microstrip antenna

Single feeding techniques are very common with microstrip antennas as they are simple, easy to manufacture, low in cost and compact in structure.

Several techniques were used to achieve circular polarization in single fed microstrip antenna. Among these techniques: fractal boundary [22, 31-35], square patch with shaped slots [7, 36, 38], embedding cross slot in metallic patch or the ground plane [38], staking antennas [30, 39], annular ring with stripline inside the inner ring [23], and truncated edges patches [4, 40].

2.5.1.1 Square patch with shaped slots

Cutting a slot in a microstrip patch antenna gives the perturbation needed to produce circular polarization. The shape and the dimensions of the cut out slot also widen the bandwidths [27, 36, 37].

2.5.1.1.1 C-shaped slot

Cutting C-shaped slot in a square patch microstrip antenna as shown in Figure 2-13 and mounting the substrate on a foam layer good circular polarization is achieved. The antenna structure is fed using aperture coupling feeding method. The dimensions of the slot are used to optimize the antenna design in the favour of axial ratio and impedance matching. The measured 3 dB axial ratio and 10 dB impedance bandwidths are 3.1 % and 16.4 % respectively [36].

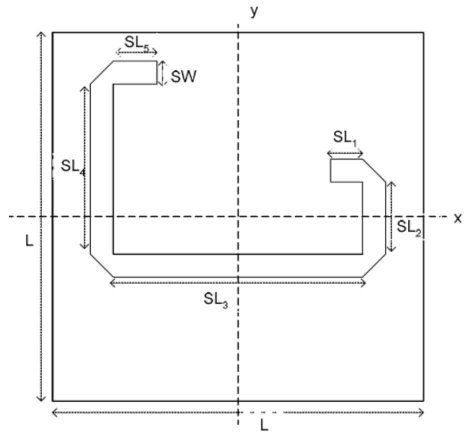


Figure 2-13 Microstrip square patch antenna with C-shaped slot [36]

2.5.1.1.2 F-shaped slot

Cutting F-shaped slot in the center of a square patch as shown in Figure 2-14 and fed with aperture coupling. Good circular polarization with 3 dB axial ratio and 10 dB impedance bandwidths are 3.2 % and 5.62 % respectively [7].

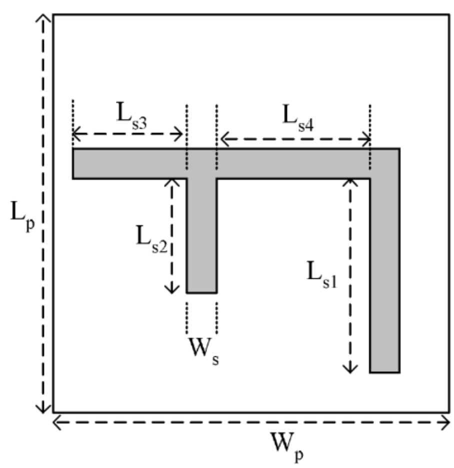


Figure 2-14 Microstrip square patch antenna with F-shaped slot [7]

2.5.1.1.3 S-shaped slot

Cutting S-shaped slot in a square patch antenna as shown in Figure 2-15 and fed with aperture coupling. Dual-band operation was obtained 3 dB axial ratio 3.6 % and 1.1 % while the 10 dB impedance bandwidths are 15 and 3.5 % respectively [38].

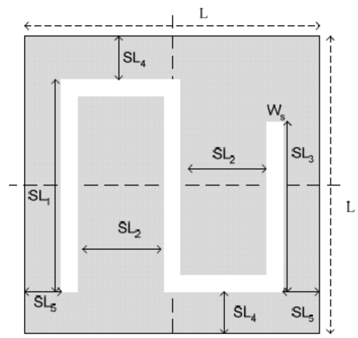


Figure 2-15 Microstrip square patch antenna with S-shaped slot [38]

2.5.1.1.4 Connected rectangular slots

Inserting two connected rectangular slots along the diagonal of a square patch microstrip antenna as shown in Figure 2-16 and feeding the structure with coaxial probe feed results in circular polarization generation. The two slots are carefully designed to generate two modes operating at very close frequency giving wide band impedance and circular polarization. The achieved 10 dB impedance bandwidth ≈ 11 % and 3 dB axial ratio bandwidth ≈ 8 % [40].

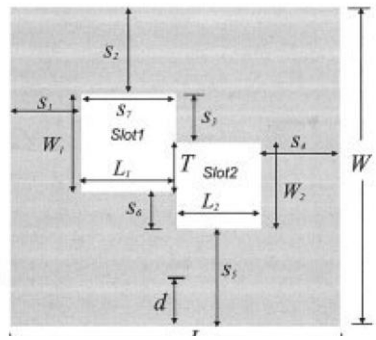


Figure 2-16 Microstrip square patch antenna with 2 connected rectangular slots [40]

2.5.1.2 Cross slot

By inserting a cross slot in a circular patch antenna as shown in Figure 2-17 circularly polarized compact size antenna is obtained. Optimizing the cross slot dimensions and the ratio between the two arms affects the axial ratio, impedance bandwidths and the antenna size dramatically. Increasing the slot length will decrease the resonant frequency hence decreasing the antenna size. The antenna is fed by proximity feed and when tested the antenna radius was 36 % smaller than antenna without the cross slot [38].

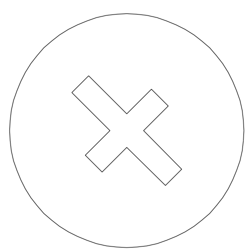


Figure 2-17 Circular patch with cross slot

The microstrip antenna with large cross slot lengths will have decreased operating frequency. But the cross slot ratio is mainly determined by the slot length, so the ratio will be close to 1 which will be difficult in fabrication. Embedding an additional equal arm cross slot in the ground plane as shown in Figure 2-18 more compact size antenna can be produced with easiness in fabrication. The ground cross slot has almost no effect on the circular polarization bandwidth. The ground cross slot reduced the operating frequency by ≈ 13 % [27].

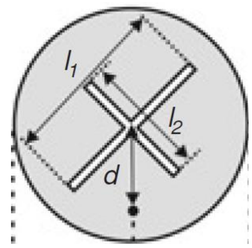


Figure 2-18 Circular patch with cross slot in the patch and ground plane [27]

2.5.1.3 Stacking antennas

Stacking microstrip antennas is used to increase the antenna bandwidth. When the antennas are designed at the same frequency, polarization increased bandwidth is achieved and when the antennas are designed at different frequencies, dual band circularly polarized antenna at both frequencies is achieved. The substrate parameters are carefully chosen to increase the bandwidth and decrease the input impedance [30, 39].

When two truncated square corners are stacked with an air gap between the two substrates as shown in Figure 2-19 dual band circularly polarized antenna is achieved [39].

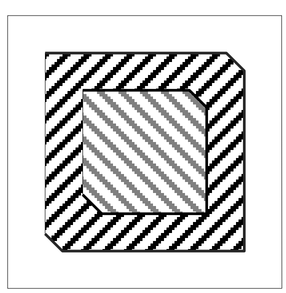


Figure 2-19 Stacked truncated corners square patches

When stacking a nearly square patch over a nearly square ring as shown in Figure 2-20 good circular polarization is excited. There is a foam layer inserted between the two substrates to help increase the bandwidth. The lower layer is fed diagonally with a coaxial cable and the upper layer is fed by proximity coupling from the lower layer. The 3 dB axial ratio bandwidth is ≈ 18.85 % and impedance bandwidth ≈ 22.13 % the circular polarization quality is excellent over the entire hemisphere [30].

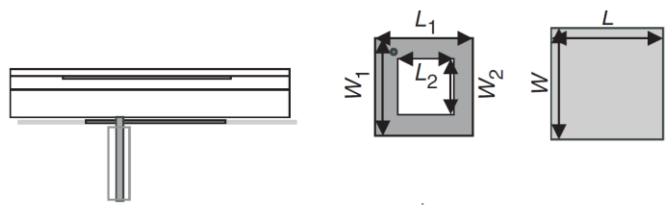


Figure 2-20 Stacked square patch over square ring [30]

2.5.1.4 Truncated edges patches

Truncated corners square microstrip patch antenna is among the first and most famous basic techniques to generate circular polarization in patch antennas. The open literature is very rich with truncated corners square microstrip antenna [4, 15, 41]. Inserting 4 equal length slits at the 4 corners of truncated corners square microstrip patch antenna as shown in Figure 2-21 gives a compact circularly polarized antenna. The size reduction is ≈ 36 % than the patch without the 4 slits [4].

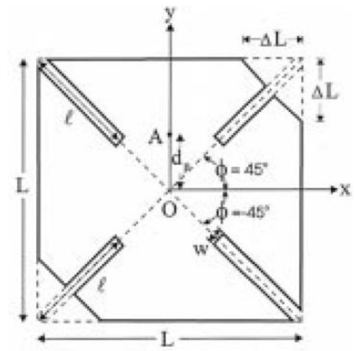


Figure 2-21 Truncated corner square microstrip antenna with 4 slits [4]

Truncated edges elliptical antenna, where opposite edges of the elliptical antenna parallel to the major axis are truncated as shown in Figure 2-22. The antenna results in circular polarization higher than the conventional elliptical antenna with 10 dB impedance bandwidth 5.7 % and 3 dB axial ratio bandwidth 1.45 %.

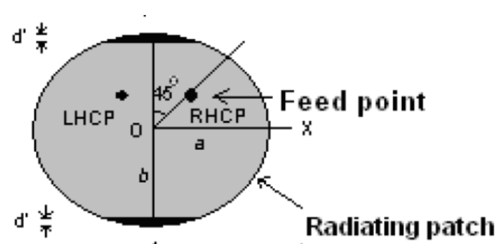


Figure 2-22 Truncated edges elliptical antenna [5]

When truncating peripheral edges from circular antenna with embedded cross slot and fed with coaxial cable as shown in Figure 2-23 produces compact circular polarization antenna [6].

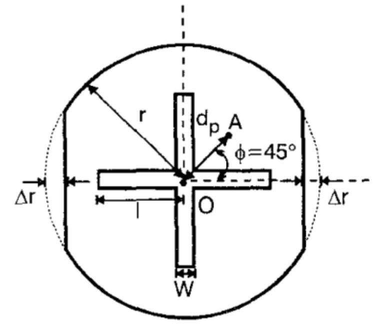


Figure 2-23 Truncated edges circular microstrip antenna [6]

2.5.1.5 Annular ring with stripline inside the inner ring

Inserting a strip line in the inner circle of an annular ring as shown in Figure 2-24 results in a compact circularly polarized microstrip antenna. The strip line is 45° to the feed and it also help in the antenna size reduction. The resonant frequency will decrease with decreasing the strip line width [23].

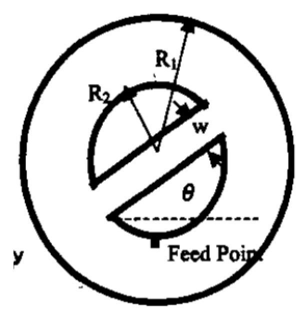


Figure 2-24 Annular ring with inner strip line [23]

2.6 Summary

This chapter discussed the components of microstrip antenna, its feeding techniques and methods of analysis. We also revised wave polarization, its kinds and its importance. The use of circularly polarized antennas presents an attractive solution to achieve this polarization match. Microstrip antenna is the most popular antenna in circular polarization generation. Circular polarization can be achieved in microstrip antenna by either using dual feed or by using perturbation segment with single feed.

Chapter 3

Truncated edges circularly polarized microstrip antenna

The proposed antenna design in this thesis uses the same approach as [4, 15, 41]. These designs introduce truncated corners/edges to square, elliptical and circular patches 45° to the feeding. Circular polarization has been introduced in circular patches through a variety of perturbation techniques such as embedding slot, inserting slits and adding stubs. The idea of truncating a circular patch antenna is presented in [6], but mainly the paper is focused on the process of compacting the antenna more than the circular polarization production. Circular patch antenna is more favorable in the array arrangement as it takes less space than rectangular patch antenna operating at the same frequency. In [6] the feeding was done via coaxial cable which needs high soldering precision. There is difficulty in using coaxial feeding with an array since a large number of solder joints will be needed. In this thesis we are going to present truncated edges circularly polarized antenna using 3 kinds of single feeding that can be used with array arrangements.

This chapter presents in details, the design methodology and steps used to design a truncated edges circularly polarized microstrip antenna. The antenna is fed by three 3 different types of single feeding (microstrip line, proximity and aperture)

3.1 Design methodology

The first stage is designing a perfect circular patch antenna operating at 2.4 GHz and its feeding network according to the type of feeding used. After determining the radius, introducing the perturbation technique then takes place. A parametric study for choosing antenna radius, the dimensions of the perturbation segments and the other antenna parameters such as the ground slot dimensions in the aperture feeding are presented explaining the chosen parameters.

3.2 Truncated edges circularly polarized antenna

The proposed antennas are based on a circular microstrip antenna. Equation (3.1) gives an initial value for the radius of a circular microstrip antenna to operate at 2.4 GHz.

$$rad = \frac{F}{\left\{1 + \frac{2h}{\pi \varepsilon_r F} \ln\left(\frac{\pi F}{2h}\right) + 1.7726\right\}^{\frac{1}{2}}} \tag{3.1}$$

where

$$F = \frac{8.791 \times 10^9}{f_r \sqrt{\varepsilon_r}} \tag{3.2}$$

rad = the patch radius, f_r = design frequency, and h = the dielectric substrate height .The substrate used is (RT/duroid 5880) with height h = 1.57 mm and εr = dielectric constant = *2.2*.

Using Equation (3.1) the antenna initial radius calculated for a perfect circular microstrip antenna operating at 2.4 GHz is equal to 23.6 mm. After determining the radius the feeding network is designed according to the type of feeding used as will be discussed in details in section 3.3, section 3.4 and section 3.5. In order to achieve circular polarization perturbation segment should be used for the generation of the two degenerate modes. In this thesis the perturbation used is to truncate two opposite edges of a circular patch with 45° angle to the feed line. Introducing these truncates will affect the antenna design parameters which may lead to changes in the calculated results such as the patch radius and the centre frequency. As will be shown later the distance between the patch centre and the perturbation segments (d) is responsible for circular polarization generation.

One of the major problems in circular polarization generation is having the best return loss and the best axial ratio at different frequencies. Antenna parameters were chosen such that to give acceptable return loss and axial ratio at the design frequency.

This thesis focuses on comparing three single feeding techniques microstrip feeding, proximity feeding, and aperture feeding. A comparison is done in terms of the axial ratio, the return loss and the radiation patterns resulting from the use of each feeding technique.

3.3 Microstrip feeding

The microstrip feed consists of a 50 Ω transmission line connected to the patch through a quarter wave length transformer to compensate the impedance difference between the patch antenna and the 50 Ω line as shown in Figure 3-1. First determining the value of perfect circular patch radius (rad) using Equation (3.1). The width of the 50 Ω line is determined using Equation (3.3).

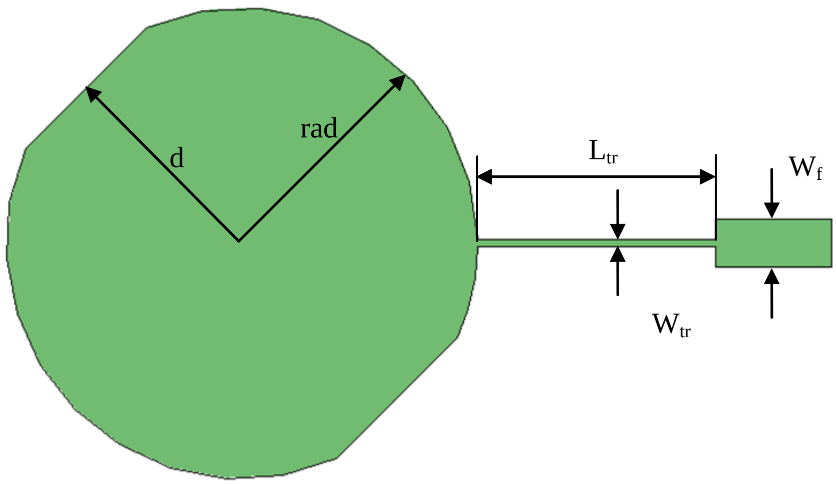


Figure 3-1 Antenna with microstrip feed

$$w_l = \begin{cases} \dfrac{8he^{A}}{e^{-2A}-2} & A > 1.52 \\ \dfrac{2h}{\pi}\left[B-1-ln(2B-1)+\dfrac{\varepsilon_r-1}{2\varepsilon_r}ln(B-1)+0.39-\dfrac{0.61}{\varepsilon_r}\right] & A < 1.52 \end{cases} \quad (3.3)$$

$$A = \frac{Z_o}{60}\left[\frac{\varepsilon_r+1}{2}\right]^{1/2} + \frac{\varepsilon_r-1}{\varepsilon_r+1}\left[0.23+\frac{0.11}{\varepsilon_r}\right] \quad (3.4)$$

$$B = \frac{60\pi^2}{Z_0} \quad (3.5)$$

The calculated width of the feed line is 4.9 mm, but usually calculations give a starting point. The feed line width calculation is refined using Rogers Corporation computer aided program MWI-2010 [43] and the feed line width is 4.88 mm. Using HFSS a perfect circle radius 23.6 mm and fed directly with 50 Ω with width (W_f) = 4.88 mm is simulated to determine the antenna impedance which is 375 Ω. To design the quarter wave length transformer its impedance has to be determined using Equation (3.6).

$$\text{Quarter wave length transformer} = \sqrt{(patch\ impedance \times Z_{\circ})} \tag{3.6}$$

The quarter wave length transformer impedance is 137 Ω and its calculated width using Equation (3.3) is 0.63 mm.

$$\text{The length of the quarter wave length transformer} = \lambda_{eff} / 4 \tag{3.7}$$

$\lambda_{eff} = \lambda_o / \sqrt{\varepsilon_{eff}}$,where λ_{eff} is the effective wavelength, λ_o is free space wave length; ε_{eff} is the effective substrate dielectric constant. According to Rogers Corporation MWI-2010 [43] the width of quarter wave length transformer is 0.61 mm, the effective wavelength = 95 mm and effective dielectric constant = 1.7494.

The circular patch antenna with the above mentioned dimensions resonates at 2.43 GHz. Since the antenna radius controls the antenna operating frequency, tweaking the antenna radius until the antenna operates at 2.4 GHz. The antenna radius and the frequency are inversely proportional, so the radius has to be increased till the resonance frequency is 2.4 GHz. A parametric study is carried out to determine the perfect circle radius. As shown in Figure 3-2 the radius that makes the antenna resonate at 2.4 GHz is 23.96 mm.

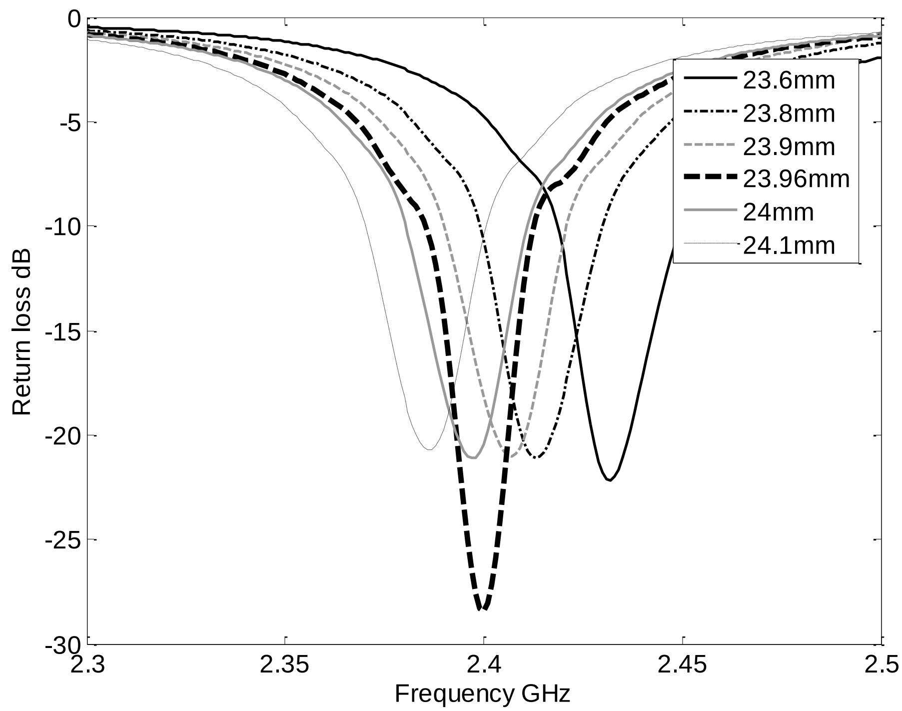
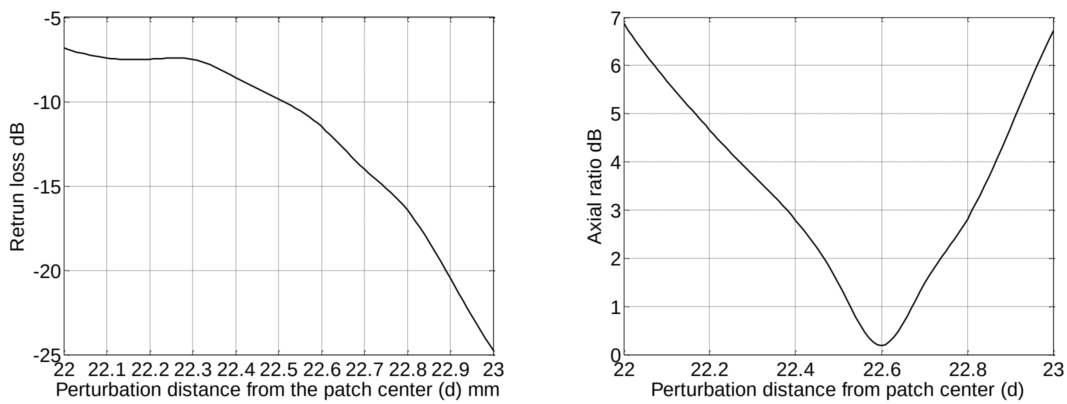


Figure 3-2 Perfect circle radius parametric study - microstrip feeding

When introducing the perturbation, another parametric study is performed to determine the optimum distance between the patch centre and the perturbation segments (d). The results of this parametric study the effect of changing (d) on the antenna return loss and axial ratio will be shown in Figure 3-3, Figure 3-4 and Figure 3-5 .

The distance (d) is chosen to give the most acceptable axial ratio and return loss at the design frequency. As shown in Figure 3-3 the best return loss and axial ratio at 2.4 GHz occurs at (d) = 23 mm, and (d) = 22.6 mm respectively. As shown in Figure 3-4 as (d) increases there are 2 modes getting closer to each other near the design frequency. As shown in Figure 3-3 with increasing (d) the axial ratio value increase till (d) = 22.6 mm it starts to decrease again and the return loss increases with increasing the value of (d). The value of (d) is chosen to be 22.6 mm. Even though much lower return loss can be achieved at higher values for (d), but the antenna at this stage is not matched yet. Further enhancement for the return loss at (d) = 22.6 mm is expected after matching, but nothing is expected to further enhance the axial ratio. After choosing the antenna radius (rad) and the perturbation distance value (d), with the help of HFSS the antenna new impedance is determined and a new quarter wave length transformer is designed.



(i)Retrun loss versus (d) (ii) Axial ratio versus (d)

Figure 3-3 Parametric analysis of (d) at 2.4 GHz - microstrip feeding

The first antenna fed with microstrip line feed parameters are, (rad) = 23.96 mm, the length of the quarter wavelength transformer (L_{tr}) = $\lambda_{eff} / 4$ = 23.5 mm, and its width (W_{tr}) = 1.15 mm, the distance between the perturbation segment and the patch center (d) = 22.6 mm, and the width of the 50 Ω line (W_f) = 4.88 mm. Antenna results will be shown in section 4.3.1.

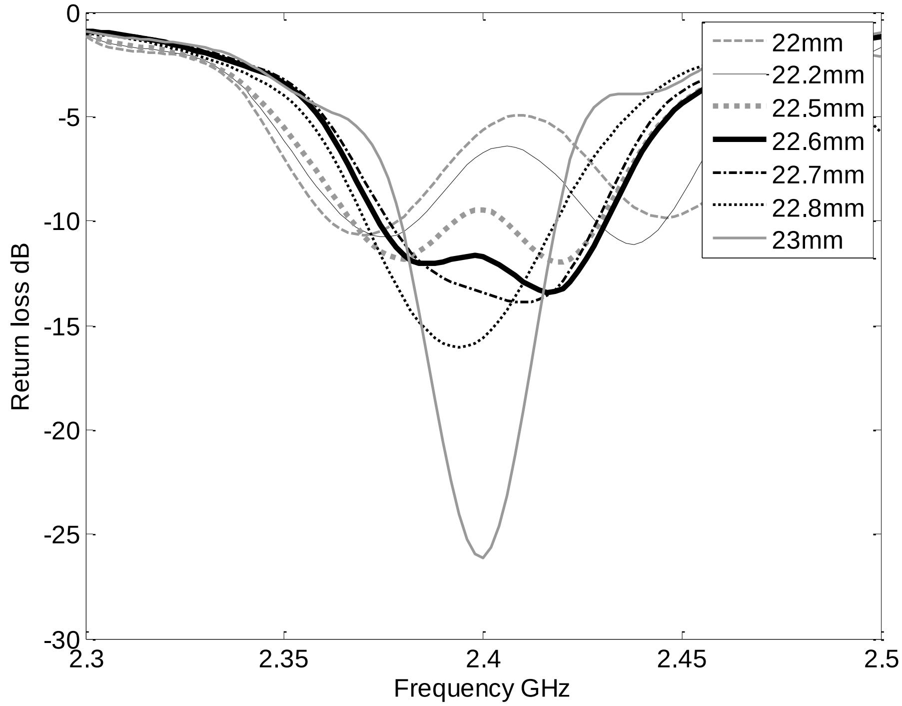


Figure 3-4 Return loss for (d) parametric study - microstrip feeding

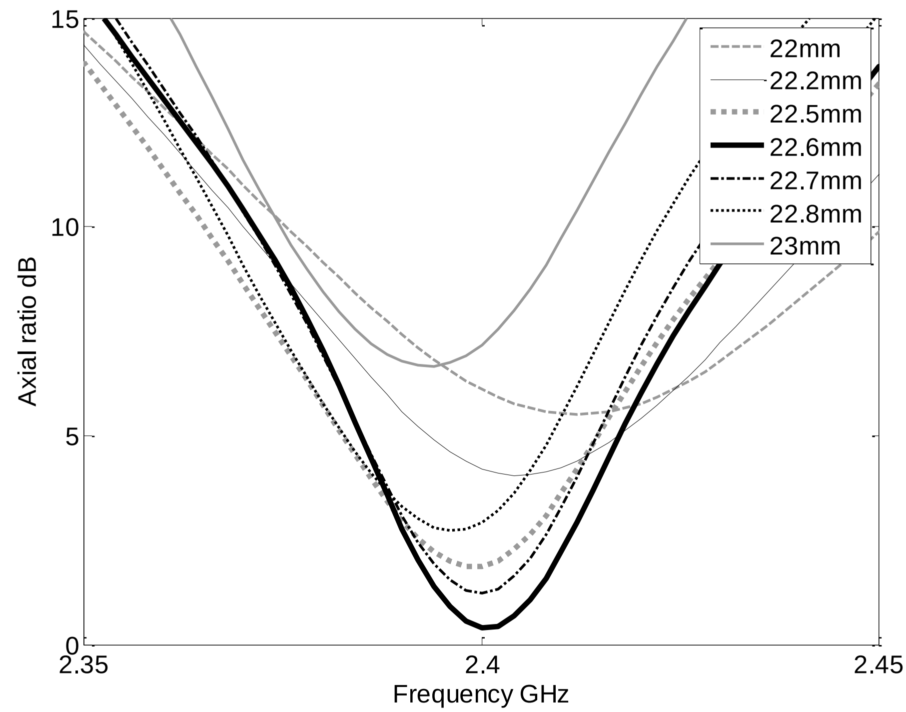


Figure 3-5 Axial ratio for (d) parametric study - microstrip feeding

3.4 Proximity feeding

The two substrates used in the proximity feeding here are the same for the antenna and the feed. The patch is located on the top of the upper substrate with no ground and the feed line is located on the top of the lower substrate with ground as shown in Figure 3-6. As been done in section 3.3, the initial value for perfect antenna radius is calculated using Equation (3.1) (rad) = 23.6 mm. The calculations for the microstrip feeding showed that the calculated width of the 50 Ω feed line is 4.9 mm, but verifying this value using HFSS the line width with 50 Ω impedance to be used with the proximity feeding is 4.62 mm.

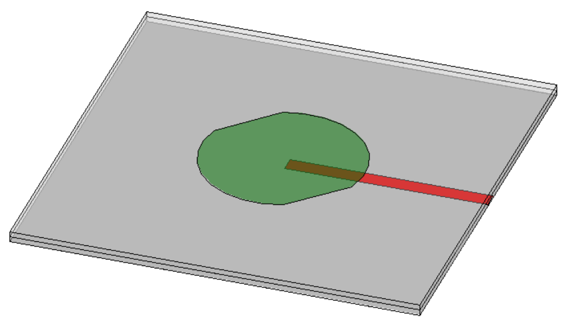


Figure 3-6 3D view for proximity fed antenna

A perfect circular patch antenna with the above mentioned dimensions as shown in Figure 3-7 resonate at 2.39 GHz, since the antenna radius controls the antenna operating frequency and the antenna radius is inversely proportional to the frequency; the antenna radius needs to be decreased. A very narrow ranged parametric study is performed as shown in Figure 3-8 to determine the perfect circle radius at 2.4 GHz. The optimum antenna radius is 23.44 mm.

When introducing the perturbation a parametric study is performed to determine the optimum distance between the patch centre and the perturbation segments (d). The results of this parametric study and the effect of changing (d) on the antenna return loss and axial ratio are shown in Figure 3-10, Figure 3-11and Figure 3-9. The distance (d) is chosen to give the most acceptable axial ratio and return loss at the design frequency.

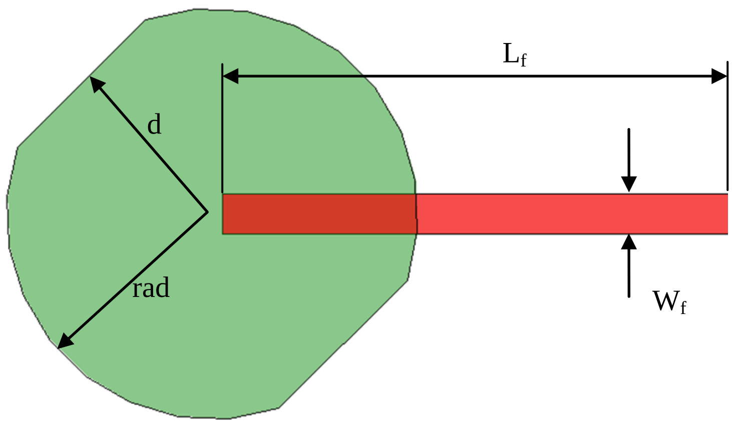


Figure 3-7 Antenna fed by proximity feeding

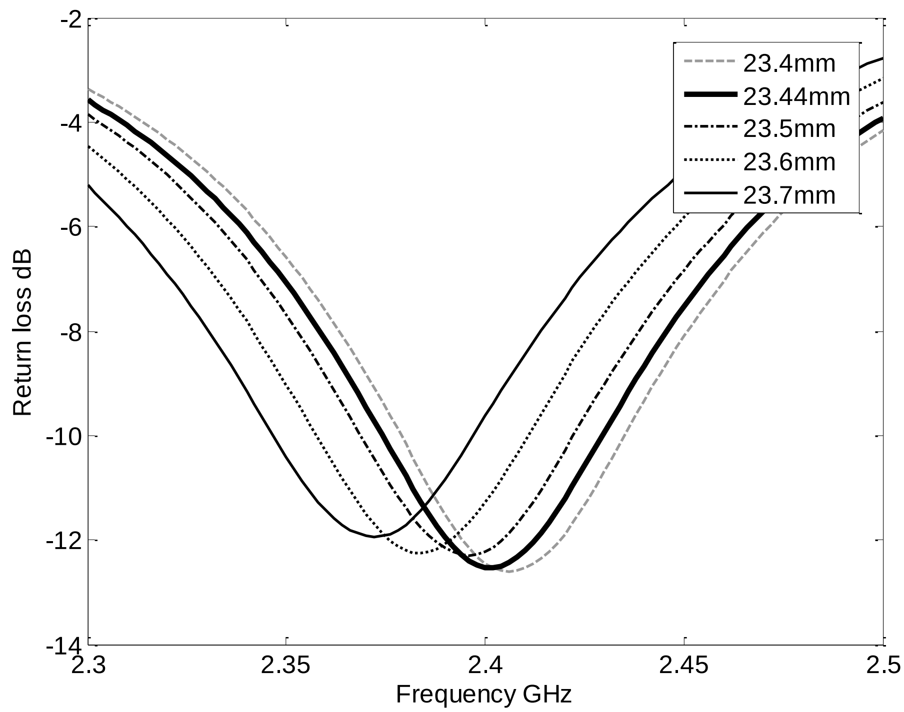
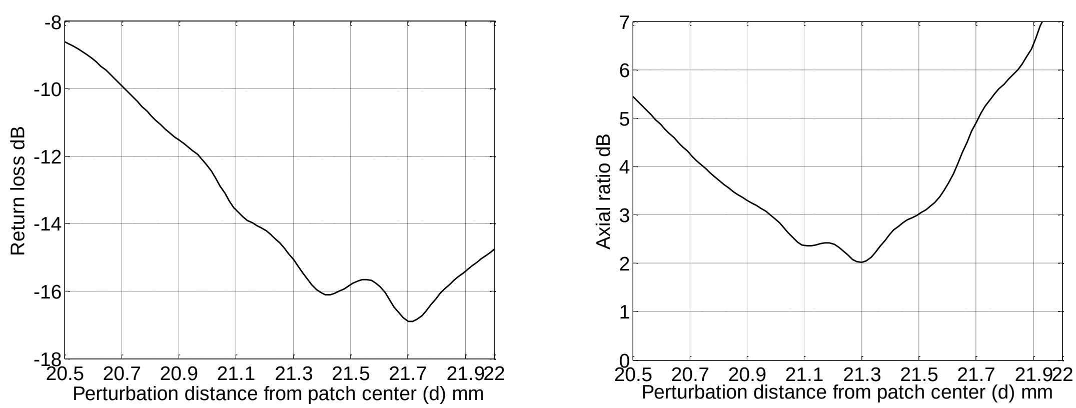


Figure 3-8 Perfect circle radius parametric study - proximity feeding

Figure 3-9 shows that the best return loss and axial ratio at 2.4 GHz occurs at (d) = 21.7 mm, and (d) = 21.3 mm respectively. Regarding Figure 3-10 and Figure 3-11 the value of (d) is chosen to be 21.4 mm. Even though 21.3 mm gives better axial ratio at 2.4 GHz, but considering Figure 3-11 (d) = 21.4 mm better return loss at 2.4 GHz and minimum axial ratio at 2.38 GHz which can shift to 2.4GHz after determining the length of the feed line or by decreasing the antenna radius .

Figure 3-10 shows that as (d) increases there are 2 modes getting closer to each other near the design frequency.

After determining the antenna radius (rad) and the perturbation distance value (d), a new parametric study is performed to choose the length of the feed line (L_f).



(i)Retrun loss versus (d) (ii) Axial ratio versus (d)

Figure 3-9 Parametric analysis of (d) at 2.4 GHz - proximity feeding

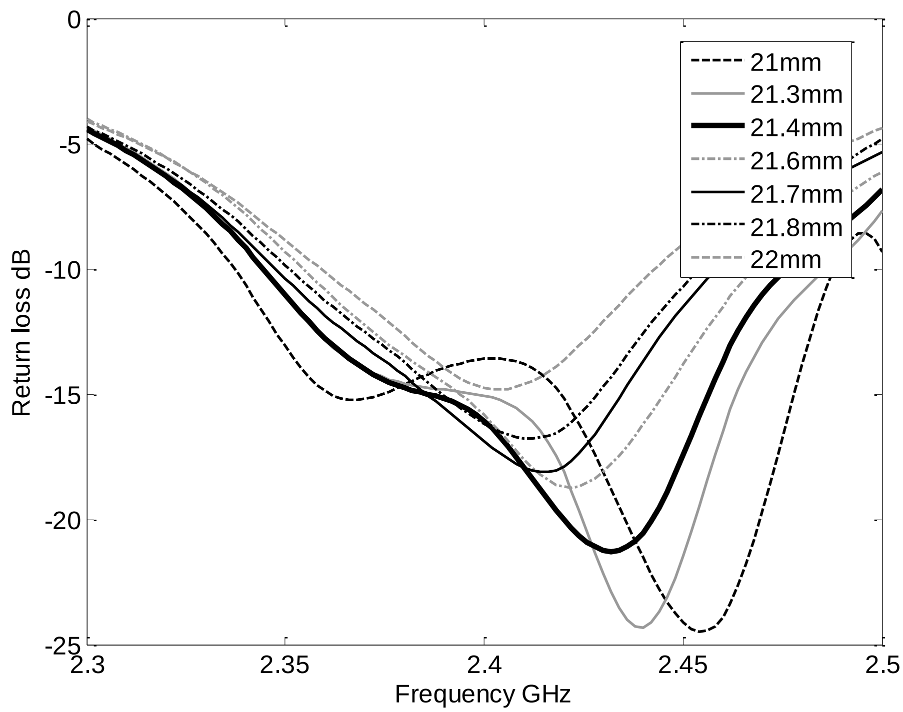


Figure 3-10 Return loss for (d) parametric study - proximity feeding

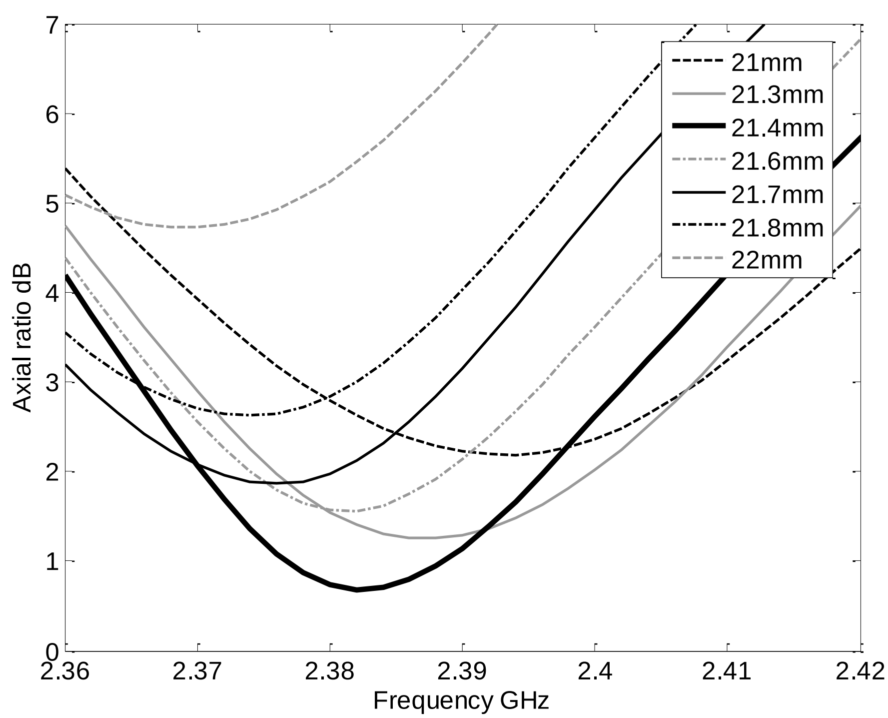
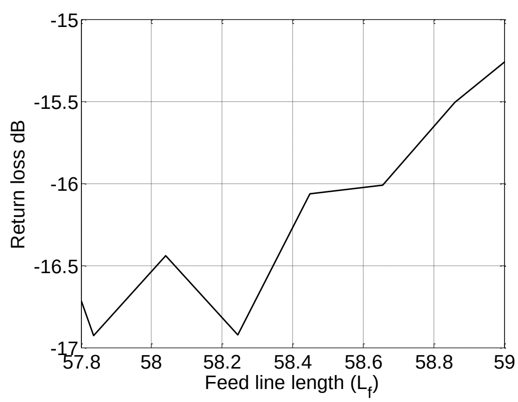
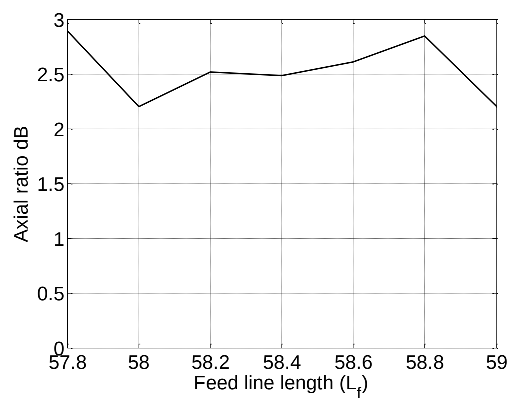


Figure 3-11 Axial ratio for (d) parametric study - proximity feeding

Figure 3-12 shows that (L_f) = 58 mm and 59 mm give the minimum value of axial ratio at 2.4 GHz, and (L_f) = 57.8 mm and 58.2 mm give the minimum value of return loss at 2.4 GHz. From Figure 3-14 the values of minimum axial ratio (L_f) = 58 mm and 59 mm give acceptable return loss values, but (L_f) = 58 mm gives better result. The feed line length is set to (L_f) = 58 mm.



(i)Retrun loss versus (L_f)



(ii) Axial ratio versus (L_f)

Figure 3-12 Parametric analysis of (L_f) at 2.4 GHz - proximity feeding

Another tuning parametric study is performed on the antenna radius (rad) to shift the minimum axial ratio to 2.4 GHz as shown in Figure 3-15 and Figure 3-16. As the value of (rad) decreases the antenna center frequency increases the values for return loss and axial ratio decreases. When (rad) is chosen to be 23.3 mm it gives a compromise between the return loss and axial ratio.

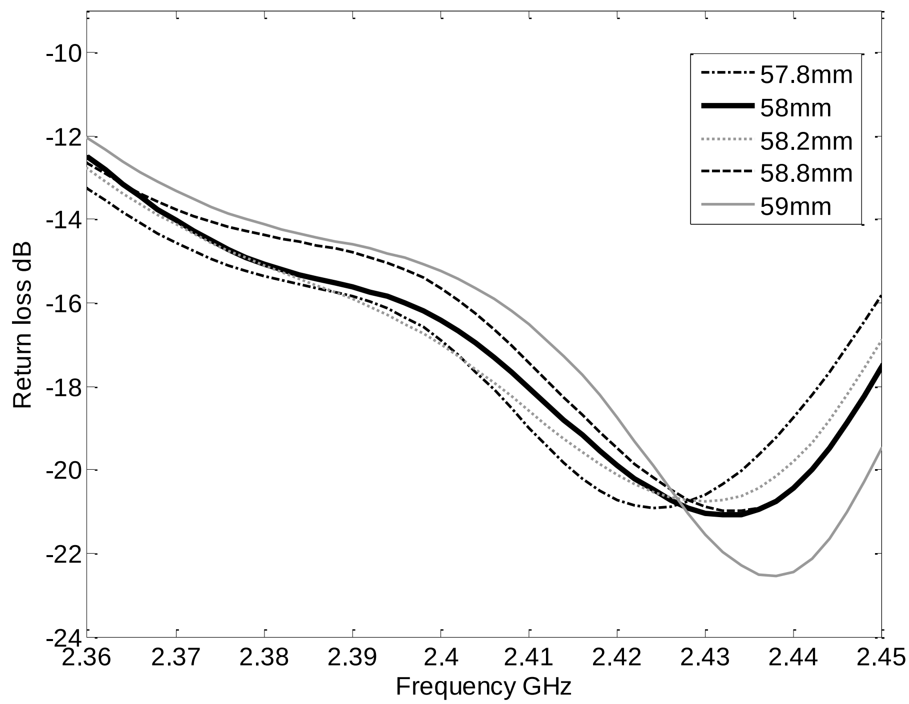


Figure 3-13 Return loss for (L_f) parametric study - proximity feeding

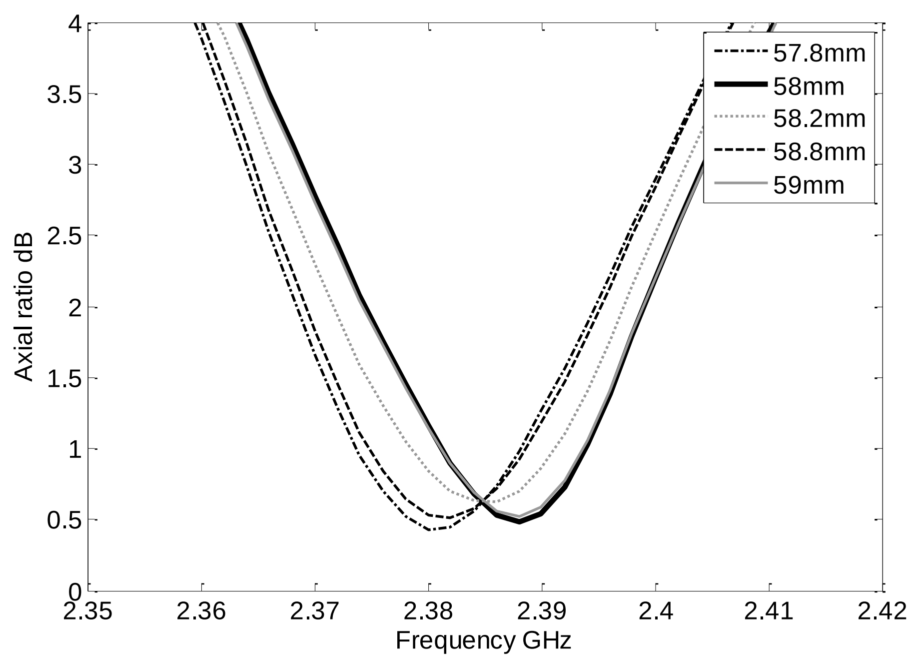


Figure 3-14 Axial ratio for (L_f) parametric study - proximity feeding

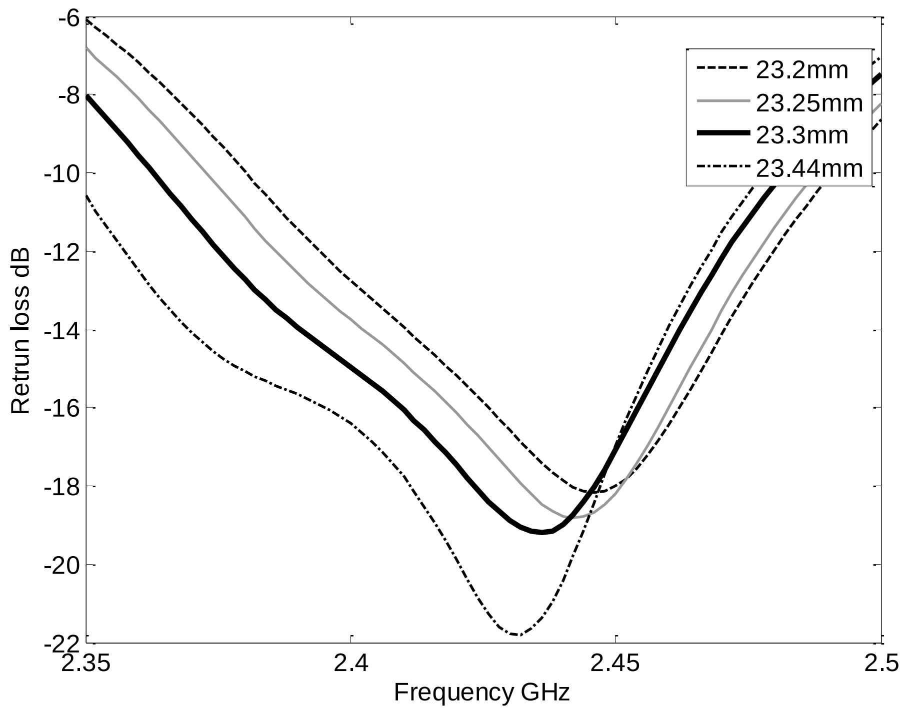


Figure 3-15 Return loss for re-determining (rad) - proximity feeding

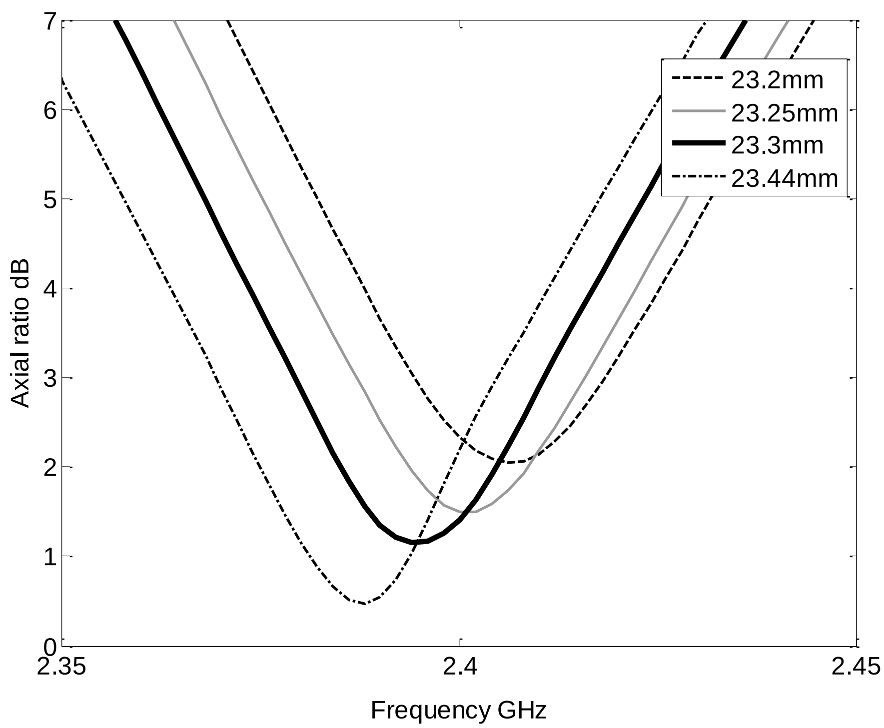


Figure 3-16 Axial ratio for re-determining (rad) - proximity feeding

After re-determining the radius (rad) another tuning may be needed for (d). Figure 3-17 and Figure 3-18 show that (d) = 21.35 mm gives better results in terms of return loss and axial ratio at 2.4 GHz. As the value of (d) increases; the value of the return loss decreases.

The second antenna fed with proximity feeding parameters are, (rad) = 23.3 mm, the distance between the perturbation segment and the patch center (d) = 21.35 mm, and the width of the 50 Ω line (W_f) = 4.62 mm. Antenna results will be shown in section 4.3.2.

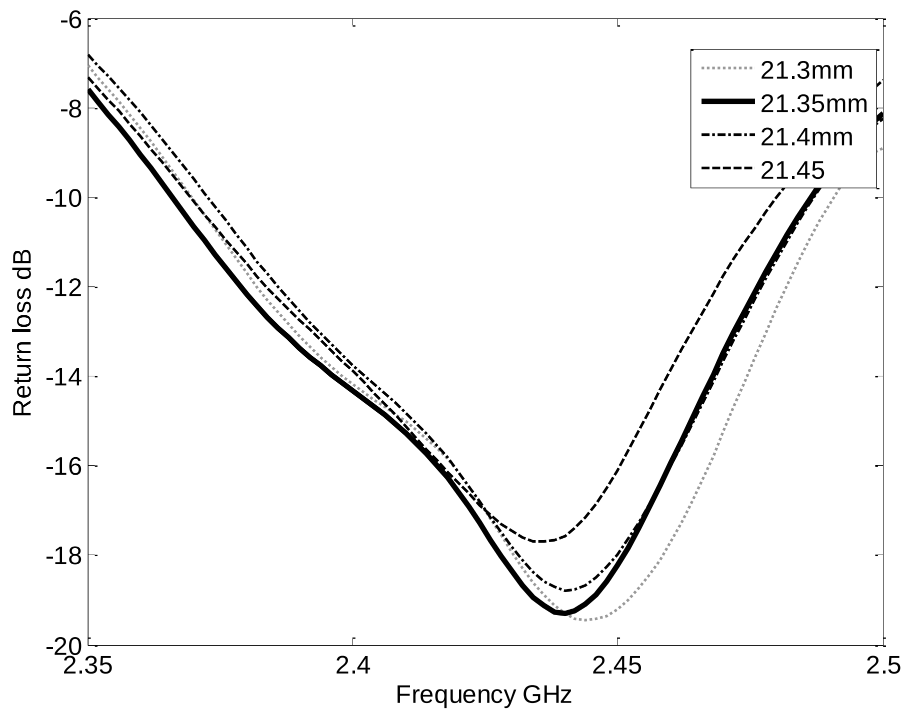


Figure 3-17 Return loss for re-determining (d) - proximity feeding

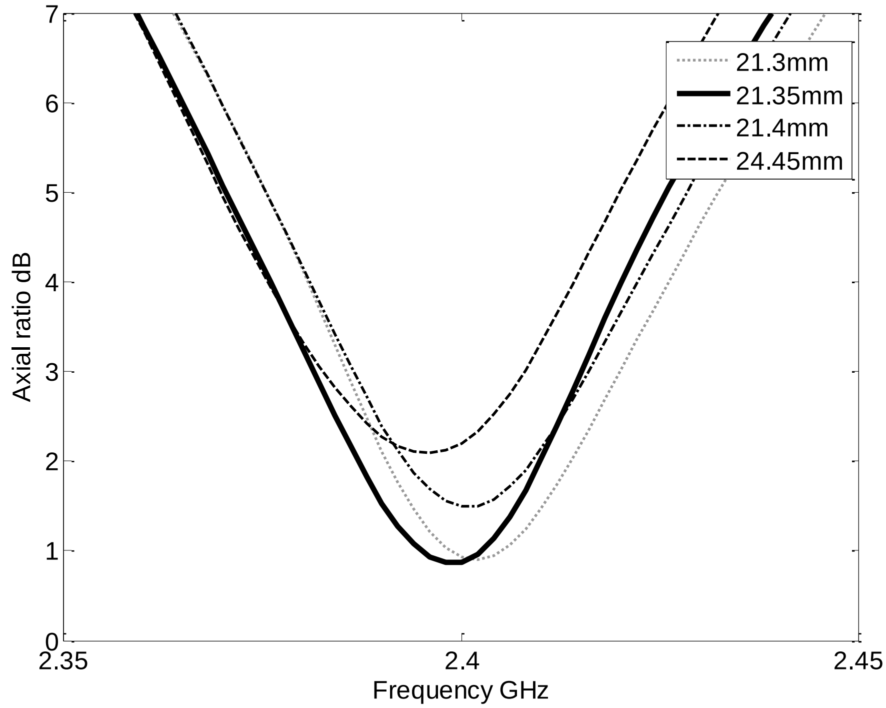


Figure 3-18 Axial ratio for re-determining (d) - proximity feeding

3.5 Aperture feeding

The two substrates used in the aperture feeding here are the same for the antenna and the feed line. The patch is located on the top of the upper substrate, the feed line is located on the bottom of the lower substrate and there is a common ground plane between the two substrates as shown in Figure 3-19. There is a slot in the common ground plane. In this thesis the slot shape is chosen circular to match the metallic patch shape selection.

As done in section 3.3 and section 3.4, the initial value for perfect antenna radius is calculated using Equation(3.1) (rad) = 23.6 mm. As the calculations for the microstrip feeding, the calculated width of the 50 Ω feed line is 4.9 mm, but verifying this value using HFSS the 50 Ω line width to be used with the aperture feeding is 4.36 mm.

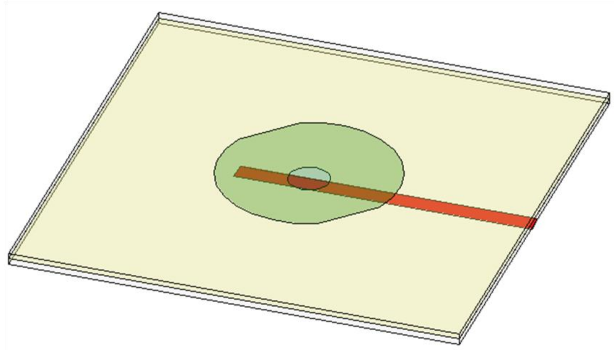


Figure 3-19 3D view for aperture fed antenna

A perfect circular patch antenna with the above mentioned dimensions as shown in Figure 3-20 resonate at 2.34 GHz. Since the antenna radius controls the antenna operating frequency and the antenna radius is inversely proportional to the frequency the antenna radius needs to be decreased. A parametric study is performed as shown in Figure 3-21 to determine the perfect circle radius at 2.4 GHz. The optimum antenna radius that resonates at 2.4 GHz is 22.99 mm.

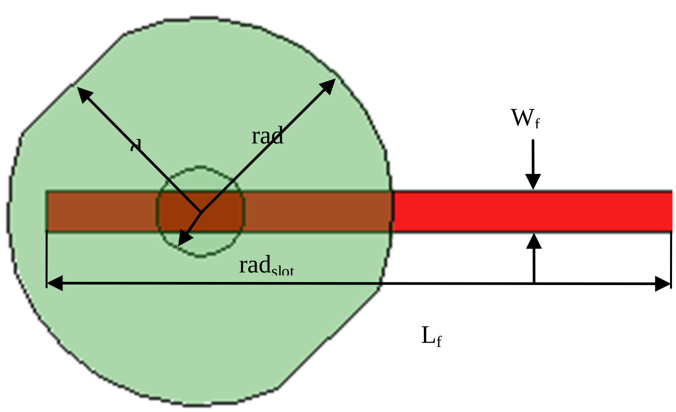


Figure 3-20 Antenna fed by aperture feeding

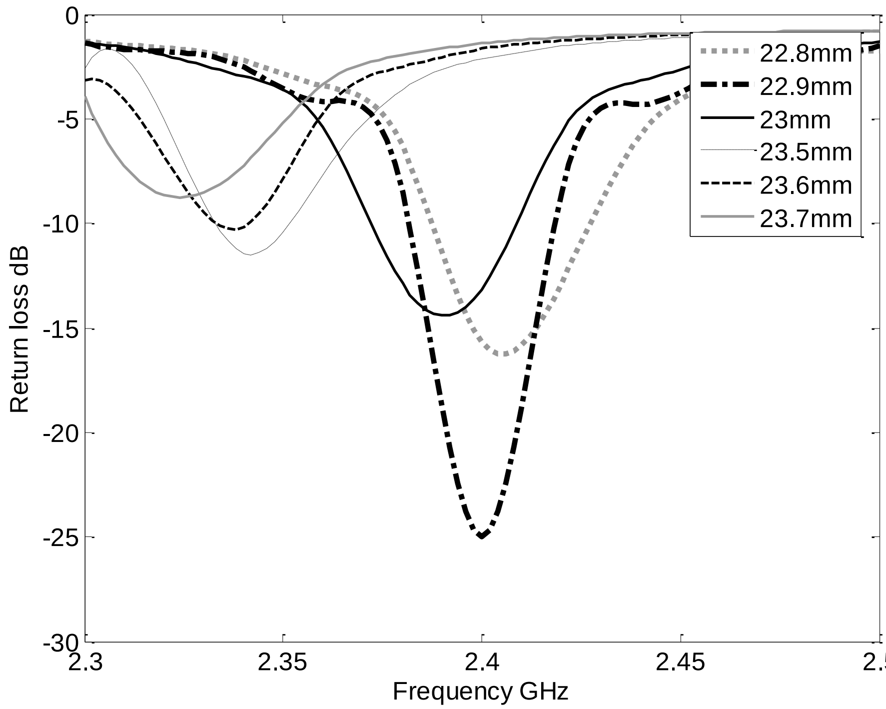
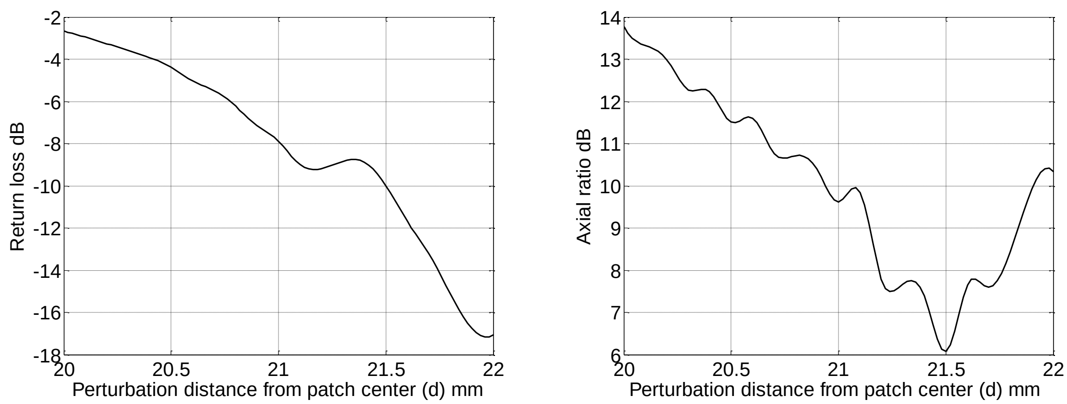


Figure 3-21 Perfect circle radius parametric study - aperture feeding

When introducing the perturbation a parametric study is performed to determine the optimum distance between the patch centre and the perturbation segments (d). The results of this parametric study and the effect of changing (d) on the antenna return loss and axial ratio are shown in Figure 3-22. Figure 3-22shows that the best return loss and axial ratio at 2.4 GHz occurs at (d) = 22 mm, and (d) = 21.5 mm respectively. As shown in Figure 3-23 as (d) increases there are 2 modes getting closer to each other near the design frequency. As shown in Figure 3-22 the best value for (d) in terms of axial ratio at 2.4GHz is 21.5 mm, which is not an acceptable value for axial ratio or return loss.



(i)Retrun loss versus (d) (ii) Axial ratio versus (d)

Figure 3-22 Parametric analysis of (d) at 2.4 GHz - aperture feeding

Also Figure 3-23 and Figure 3-24 show that (d) = 22 mm gives acceptable return loss at 2.4 GHz, but not acceptable value for the axial ratio. At 2.42 GHz some values for (d) give acceptable axial ratio, but not good return loss at the same value for (d). As a matter of the fact the antenna is not yet matched and there are still two parametric studies for the feed line length and the slot radius to be performed. So (d) is chosen to be 21.6 mm as it has an acceptable axial ratio at 2.42 GHz and the return loss curve minimum occurs at 2.4 GHz.

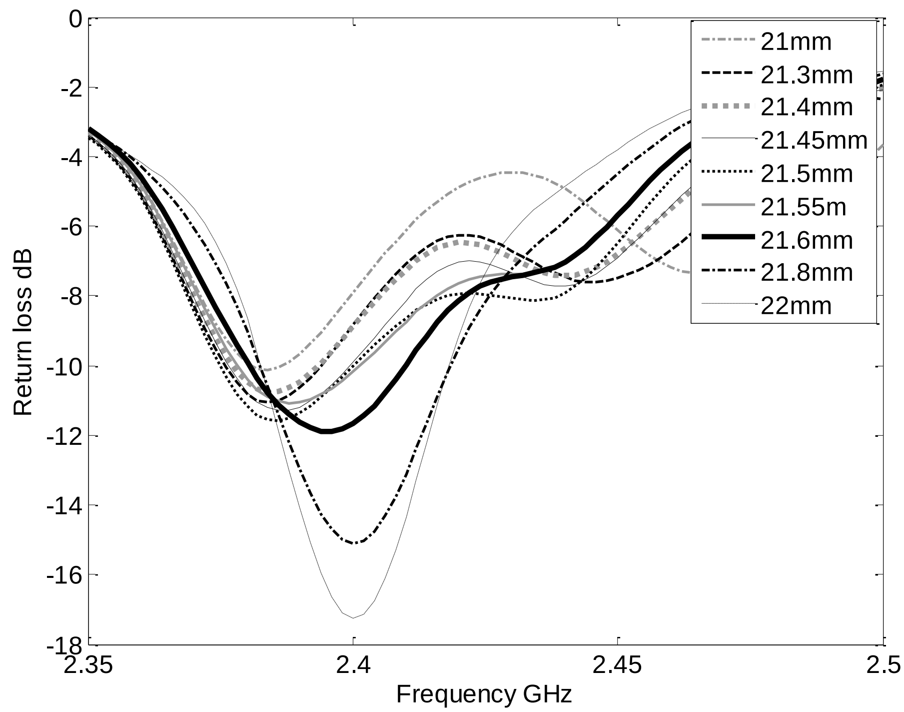


Figure 3-23 Return loss for (d) parametric study - aperture feeding

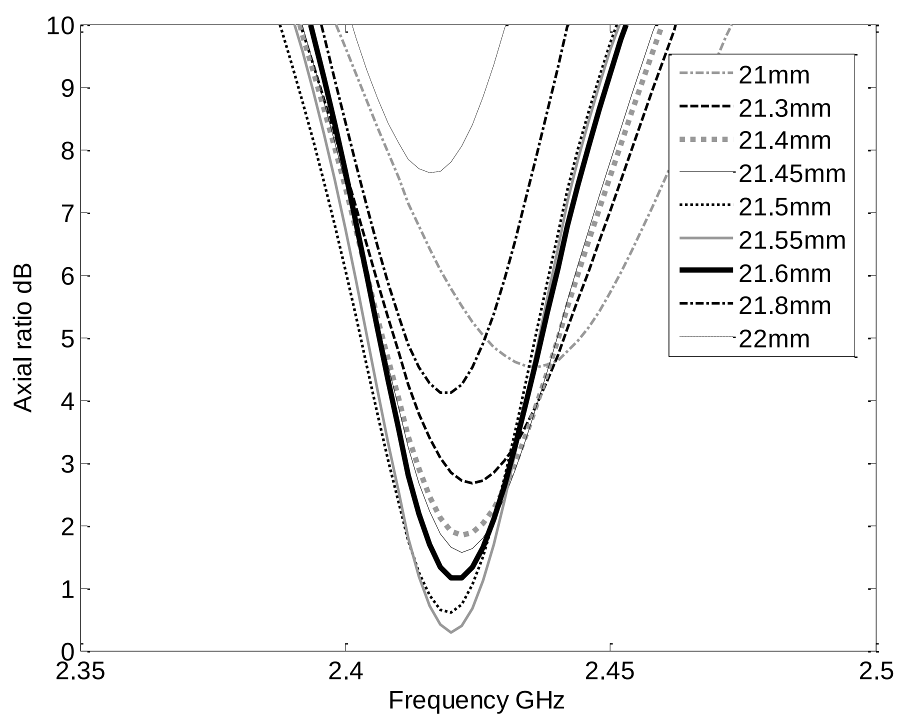
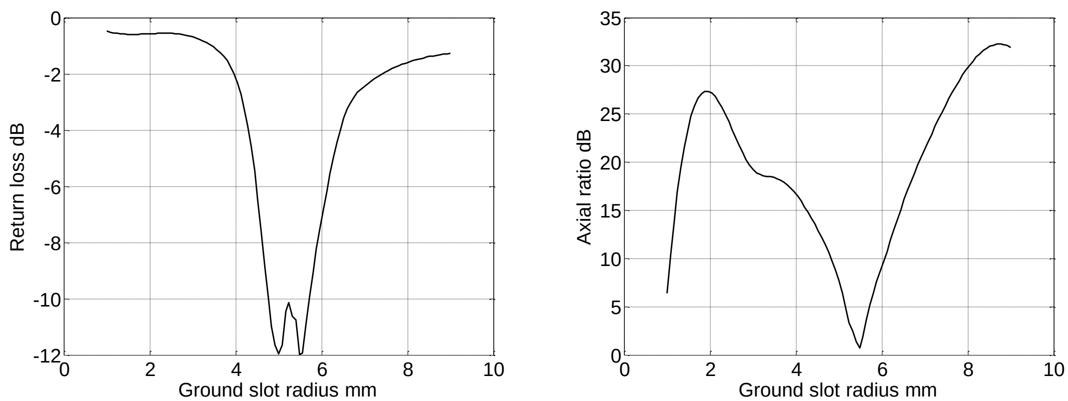


Figure 3-24 Axial ratio for (d) parametric study - aperture feeding

Weather the effect of the slot radius and the feed line length will improve the axial ratio and return loss of the antenna at 2.4 GHz or not will be shown in the following parametric studies.



(i)Retrun loss versus (rad_{slot})   (ii) Axial ratio versus (rad_{slot})

Figure 3-25 Parametric analysis of (rad_{slot}) at 2.4 GHz - aperture feeding

Figure 3-25 shows that changing the radius of the ground plane slot (rad_{slot}) affects both the axial ratio and return loss. The figure also shows that the best values for axial ratio and return loss at 2.4GHz occurs at (rad_{slot}) = 5.5 mm although the value for return loss is acceptable, but not good. Figure 3-26 shows that when (rad_{slot}) = 5.5 mm, the minimum value of the curve is not at 2.4 GHz it is at 2.37 GHz. Figure 3-27 shows that when (rad_{slot}) = 5.5 mm, the minimum value of the curve is at 2.4 GHz with a very good axial ratio value. Since the antenna still has one more parametric study for the length of the feed line which will affect the return loss at the design frequency (rad_{slot}) is set to 5.5 mm.

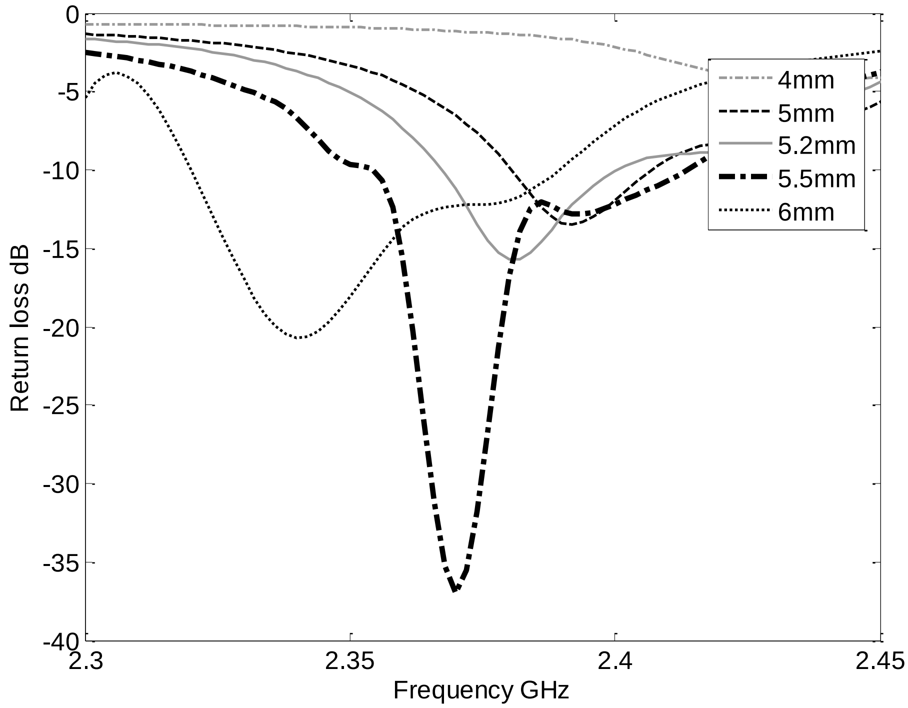


Figure 3-26 Return loss for (rad_{slot}) parametric study - aperture feeding

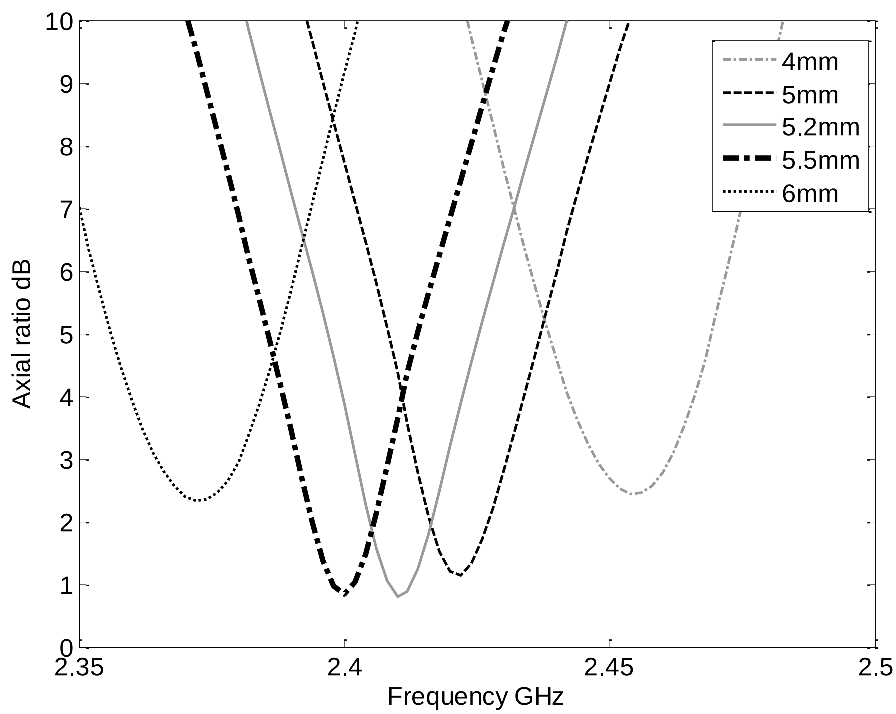
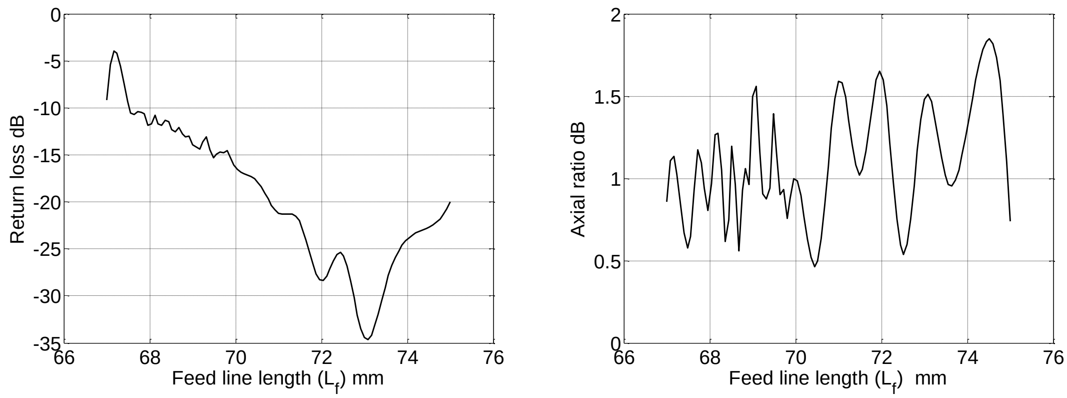


Figure 3-27 Axial ratio for (rad_{slot}) parametric study - aperture feeding



(i)Retrun loss versus (L_f) (ii) Axial ratio versus (L_f)

Figure 3-28 Parametric analysis of (L_f) at 2.4 GHz - aperture feeding

Figure 3-28 shows that changing the length of the feed line (L_f) affects the return loss and doesn't have much effect on the axial ratio. The figure also shows that by increasing the value of the feed line the return loss value increases at 2.4 GHz till a certain value where (L_f) = 73 mm it reverse. Starting from (L_f) = 68 mm all the axial ratio and return loss values are accepted at 2.4 GHz. Figure 3-29 shows that at (L_f) = 72.5 the return loss value at 2.4 GHz is very good, and Figure 3-30 shows that at the same value (L_f) = 72.5 mm the value of axial ratio is very good and centered at 2.4 GHz.

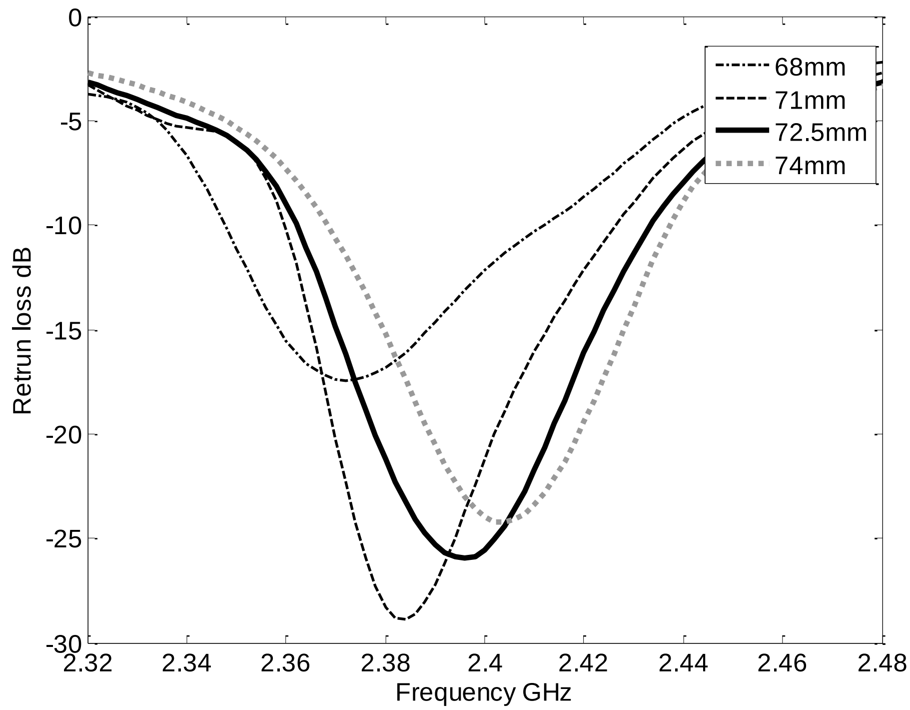


Figure 3-29 Return loss for (L_f) parametric study - aperture feeding

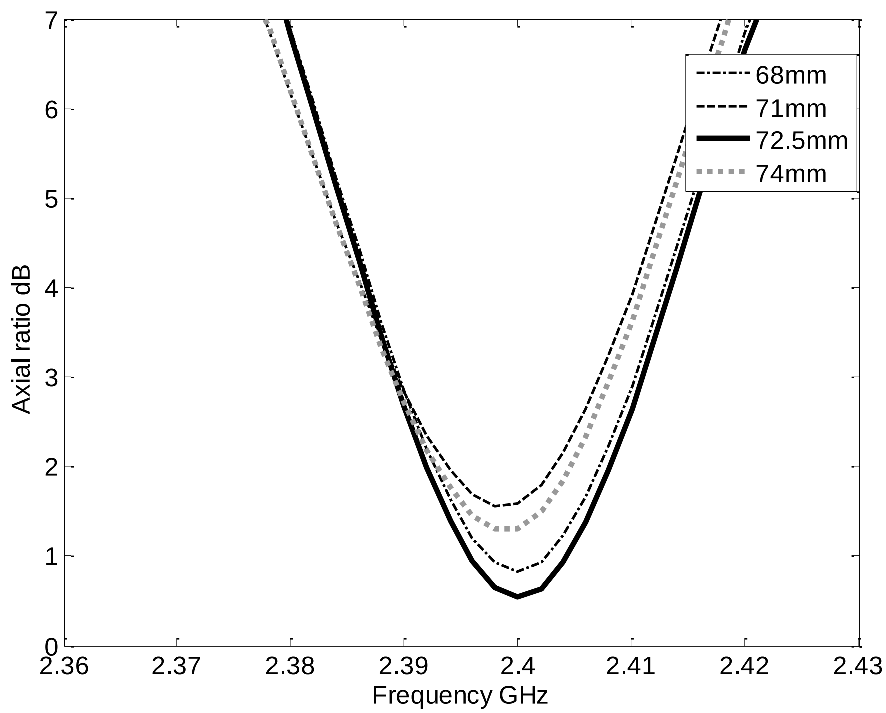


Figure 3-30 Axial ratio for (L_f) parametric study - aperture feeding

The second antenna fed with aperture feeding parameters are; (rad) = 22.9 mm, the distance between the perturbation segment and the patch center (d) = 21.6 mm, and the width of the 50 *Ω* line (W_f) = 4.36 mm. Antenna results will be shown in section 4.3.3.

3.6 Summary

Calculated circular patch radius at 2.4 GHz was the initial point to the antenna design.

Carrying out a parametric study for each variable in order to choose the optimum values for the design. For microstrip fed antenna a parametric study for the circular patch radius (rad) and the distance between the patch center and the perturbation segment (d) were carried out. For the proximity fed antenna more parametric studies were carried out, for (rad), (d) and the length of the 50 *Ω* feed line (L_f). For the aperture fed antenna also more parametric studies were carried out, for (rad), (d), (L_f) and the ground slot radius (rad_{slot}).

The increase of parametric studies also increases the complexity of antenna design and fabrication.

Chapter 4

Antenna design results and verifications

This chapter presents design verification for the 3 designed antennas using CST [44] software and measured prototype. It also discusses the HFSS [42] simulation results of the 3 antennas in terms of return loss, axial ratio and radiation patterns. It also presents a comparison between the 3 antennas dimensions and radiation output.

4.1 Design verification for the 3 proposed antennas

After going through all the parametric studies and finalizing the design parameters for each antenna, the verification of the final design takes place using CST software. Figure 4-1 shows the return loss versus frequency simulation for the microstrip fed antenna using HFSS and CST. The figure shows that there is a difference between the results of the two software simulations, but this difference is within the acceptable range. Both simulators give a good return loss at 2.4 GHz.

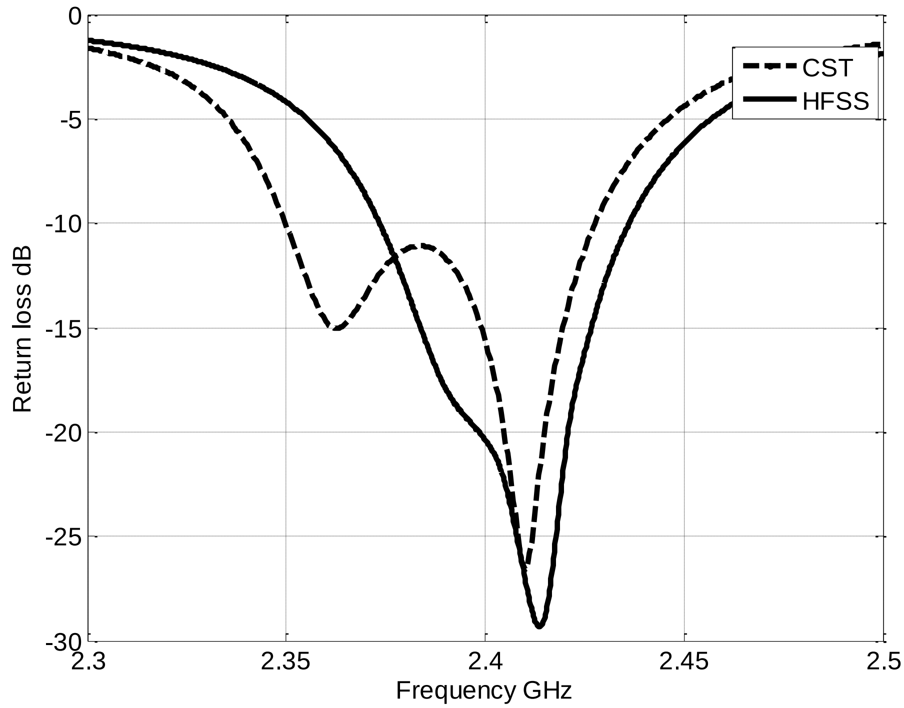


Figure 4-1 Microstrip line fed antenna HFSS-CST verification

For the antenna fed by proximity feeding Figure 4-2 shows the return loss versus frequency simulation using HFSS and CST. The figure shows that there is a difference between the results of the two software simulations, but this difference is within the acceptable range. Both simulators give a good return loss at 2.4 GHz.

Also Figure 4-3 shows the return loss versus frequency simulation for the aperture fed antenna using HFSS and CST. The figure shows that there is a difference between the results of the two software simulations. Both simulators give a good return loss at 2.4 GHz.

From Figure 4-1, Figure 4-2 and Figure 4-3 there is a trend that the CST results are shifted to a lower frequency than HFSS.

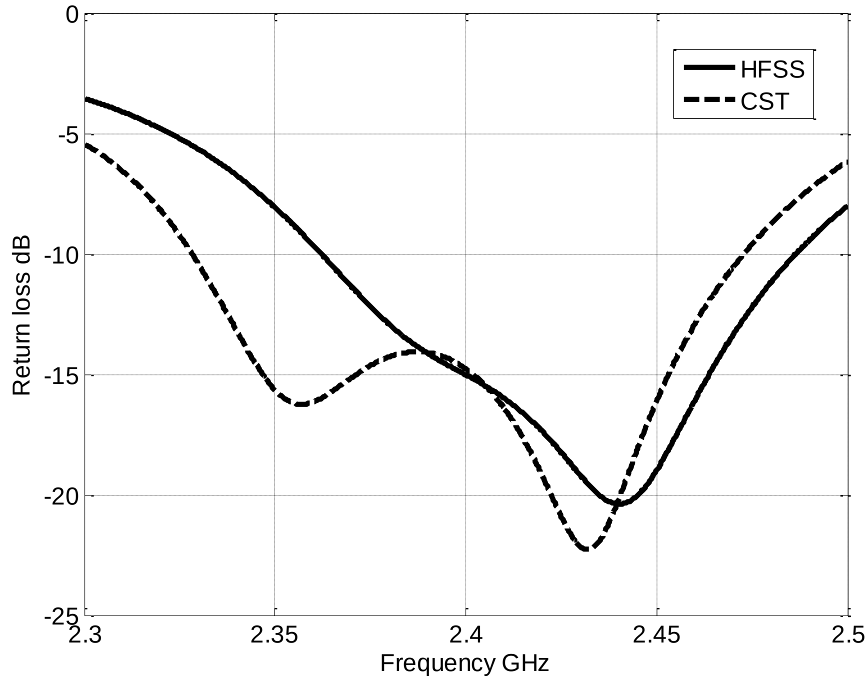


Figure 4-2 Proximity fed antenna HFSS-CST verification

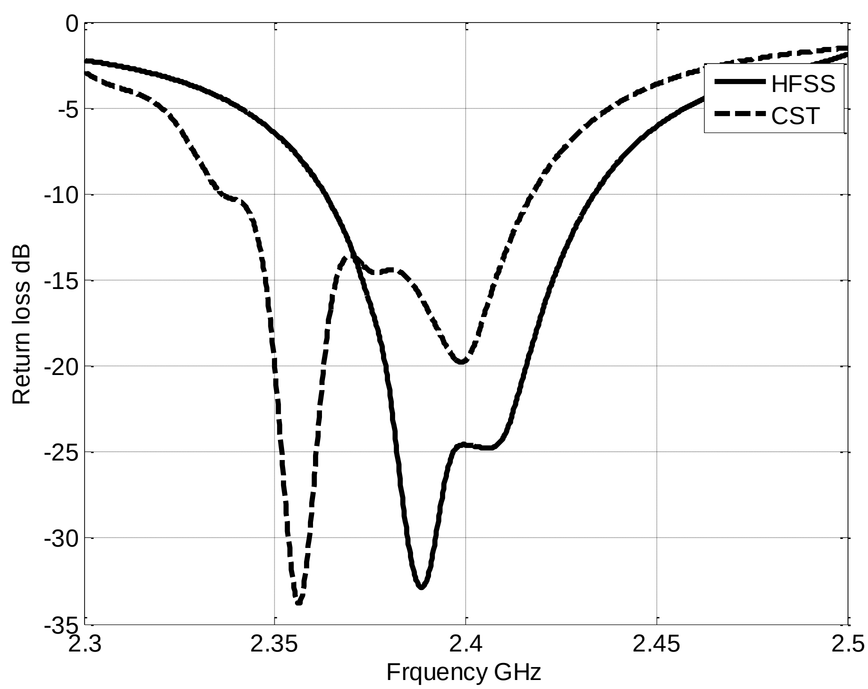


Figure 4-3 Aperture fed antenna HFSS-CST verification

4.2 Fabrication and measured results

The microstrip fed antenna shown in Figure 4-4 was fabricated by mechanical milling on RT/duriod 5880. Figure 4-5 shows a comparison between the return loss results produced by HFSS simulator, CST simulator and measured by Agilent Technologies E8364B PNA network analyzer.

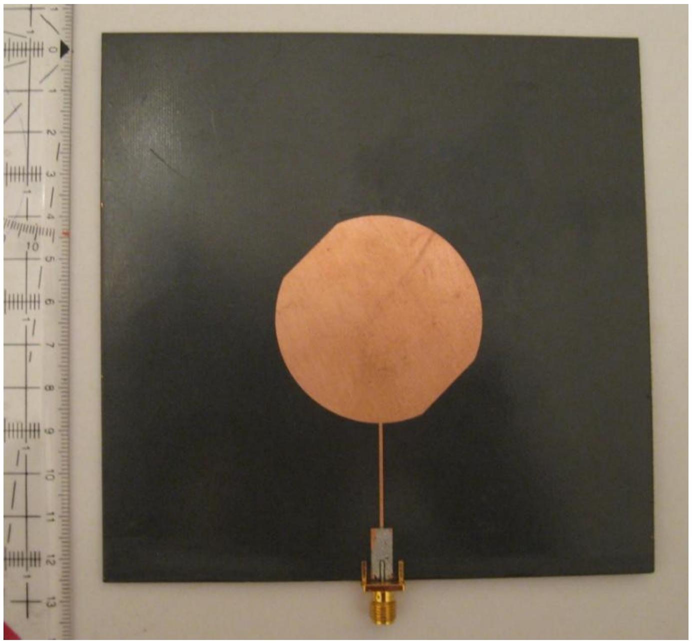


Figure 4-4 fabricated microstrip fed antenna

Figure 4-5 shows a comparison between the actual return loss measured results and the simulation results obtained using HFSS and CST. It can be seen that the measured results and the HFSS results achieve the minimum return loss at the same frequency 2.415 GHz; however the measured results and the CST results follow the same curve shape. The measured results shows the antenna has two resonant frequencies 2.365 GHz and 2.415 GHz. The presence of two resonant frequencies is due to the excitation of two different modes. These two modes are responsible for the production of circular polarization at the frequency between these two frequencies. The obtained results from the simulation confirm its presence at 2.4 GHz.

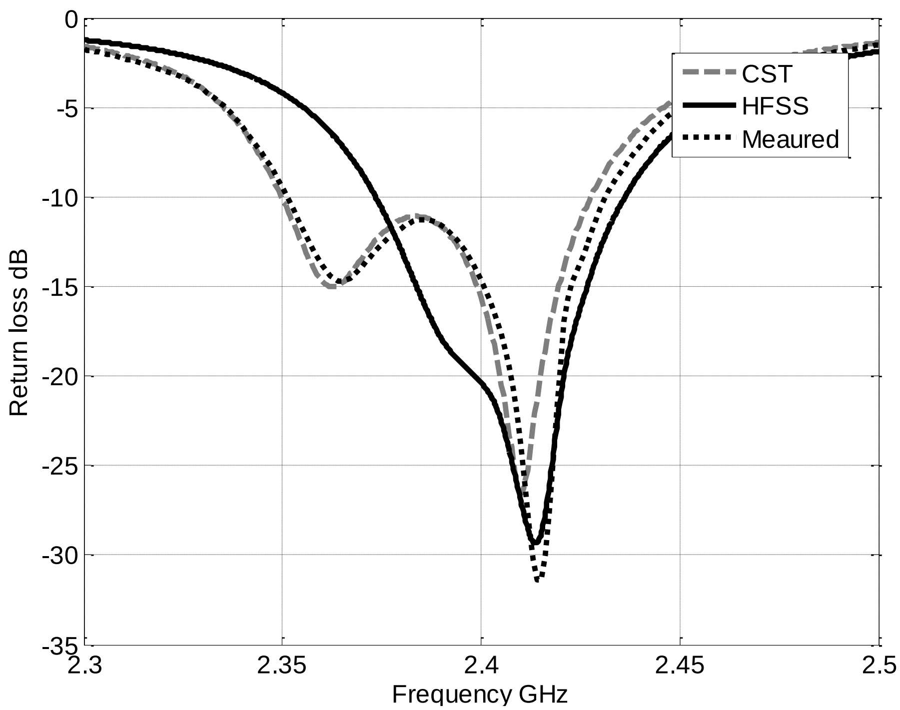


Figure 4-5 Return loss versus frequency for fabricated antenna fed with microstrip line

4.3 HFSS simulation results for the 3 proposed antennas

4.3.1 Microstrip feeding

The final design parameters of the antenna fed by microstrip line as shown in Figure 3-1 is simulated by HFSS and verified by CST. Figure 4-6shows the antenna return loss versus frequency with 10 dB impedance bandwidth is 2.92 % using HFSS. Figure 4-7 shows the antenna axial ratio versus frequency with 3 dB axial ratio bandwidth is 0.833 %. The microstrip line fed antenna yields directive gain 8.11 dB gain.

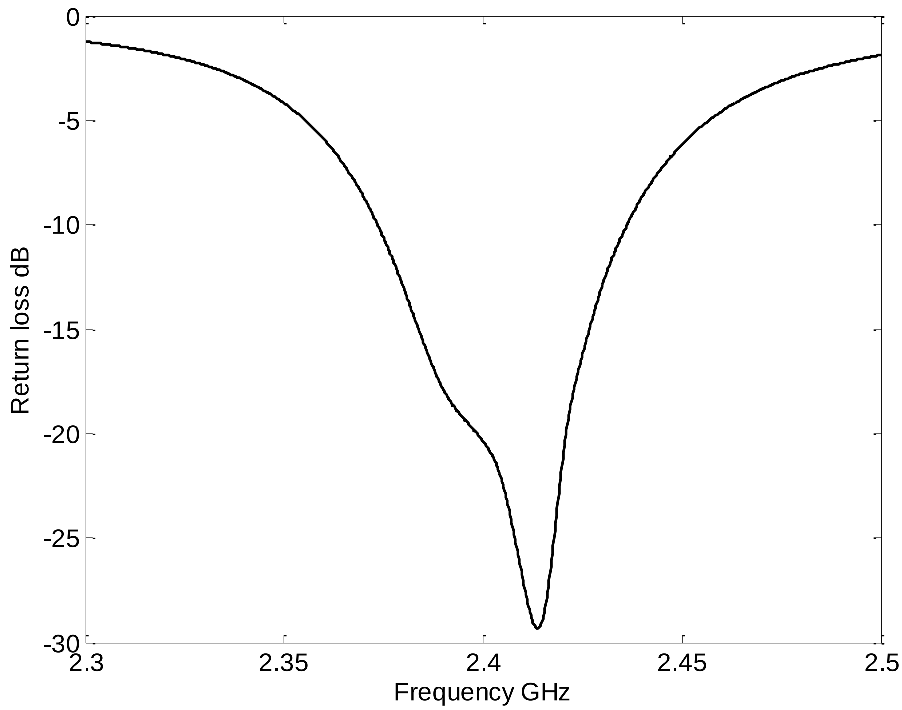


Figure 4-6 Return loss for antenna fed with microstrip line vs. frequency

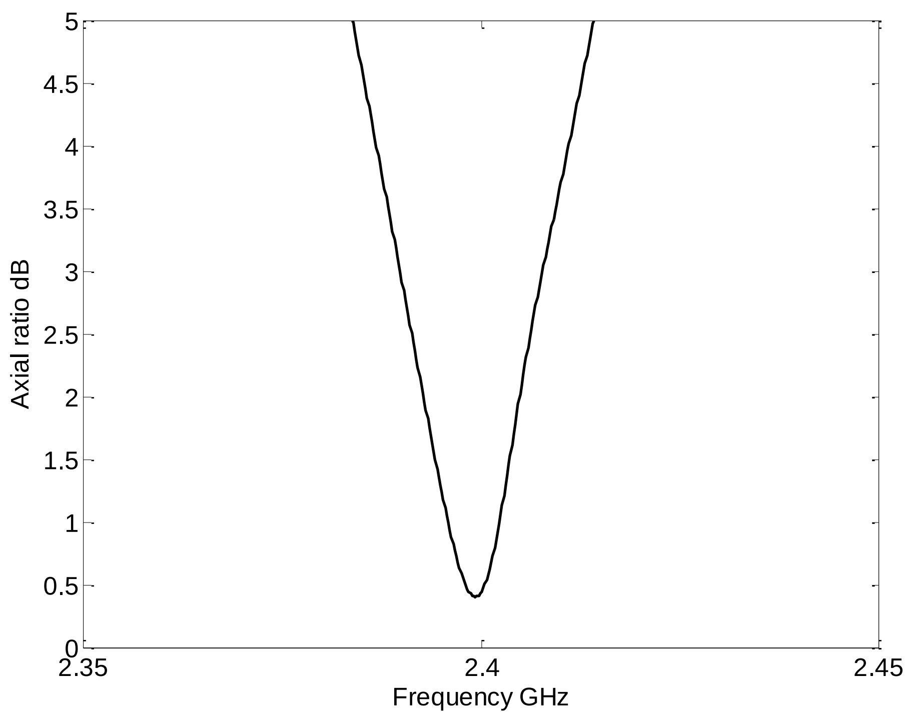


Figure 4-7 Axial ratio for antenna fed with microstrip line feed vs. frequency

The co and cross-polarization in the E-plane and H-plane are presented in Figure 4-8 and Figure 4-9 respectively using HFSS. The figures show that the antenna is right hand circularly polarized with half power beamwidth ≈ 70° in the E-plane(φ = 0°, 180°) and ≈ 73°in H-plane (φ = 90°, 270°).

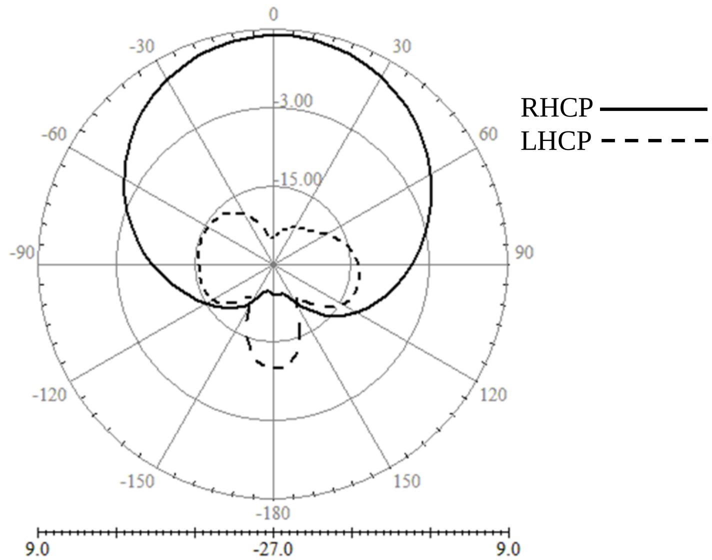


Figure 4-8 E-plane radiation pattern for microstrip line fed antenna @ f_r = 2.4GHz

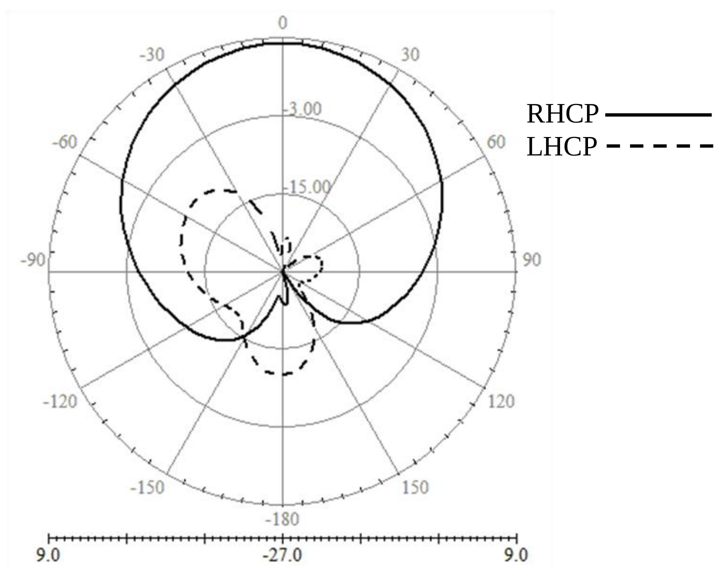


Figure 4-9 H-plane radiation pattern for microstrip line fed antenna @f_r = 2.4GHz

The difference between the co and cross-polarization in both the E and H-planes ≈ 31.08 dB which is considered good isolation.

4.3.2 Proximity feed line

The final design parameters of the antenna fed by proximity feeding shown in Figure 3-7 is simulated by HFSS and verified by CST. Figure 4-10 shows the antenna return loss versus frequency with 10 dB impedance bandwidth is 5.36 %. Figure 4-11 shows the antenna axial ratio versus frequency with 3 dB axial ratio bandwidth is 1.45 %. The impedance and axial ratio bandwidth percentage in the proximity feeding is almost double that in the microstrip feeding.

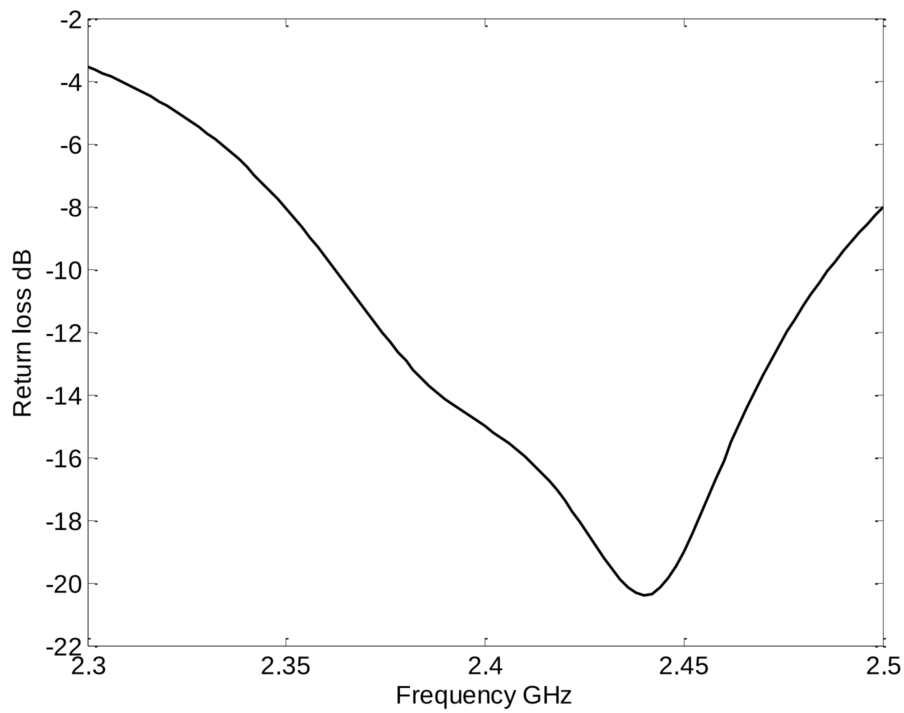


Figure 4-10 Return loss for antenna fed with proximity feeding vs. frequency

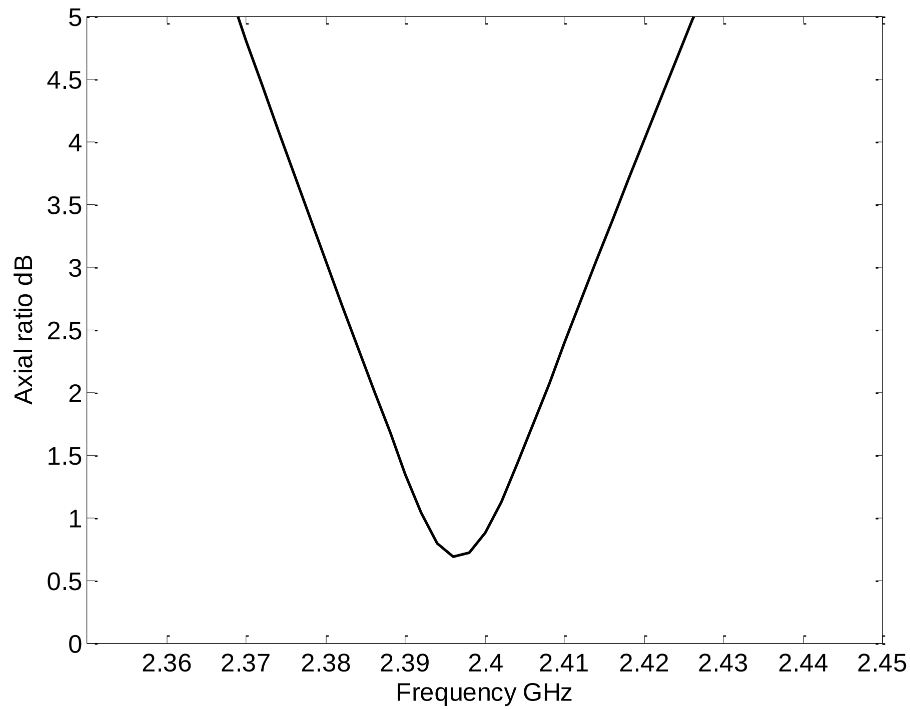


Figure 4-11 axial ratio for antenna fed with proximity feed vs. frequency

Figure 4-12 and Figure 4-13 show the co- and cross-polarization in the E-plane (φ = 0°, 180°) and H-plane (φ = 90°, 270°) respectively using HFSS. The figures show that the antenna is right hand circularly polarized with half power beamwidth ≈ 70° in the E-plane and ≈77.5°in H-plane. The difference between the co and cross-polarization in both the E and H-planes ≈ 28.14 dB, which is considered good isolation. The proximity fed antenna directive gain is 8 dB.

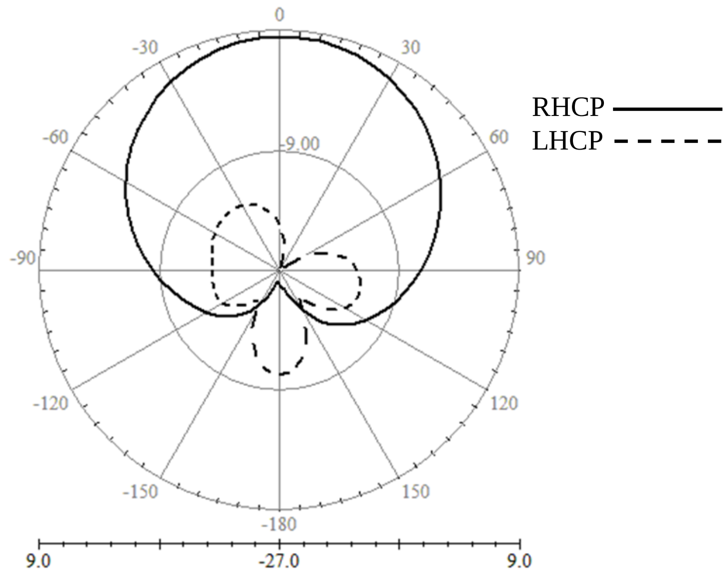


Figure 4-12 E-plane radiation pattern for proximity fed antenna @f_r = 2.4GHz

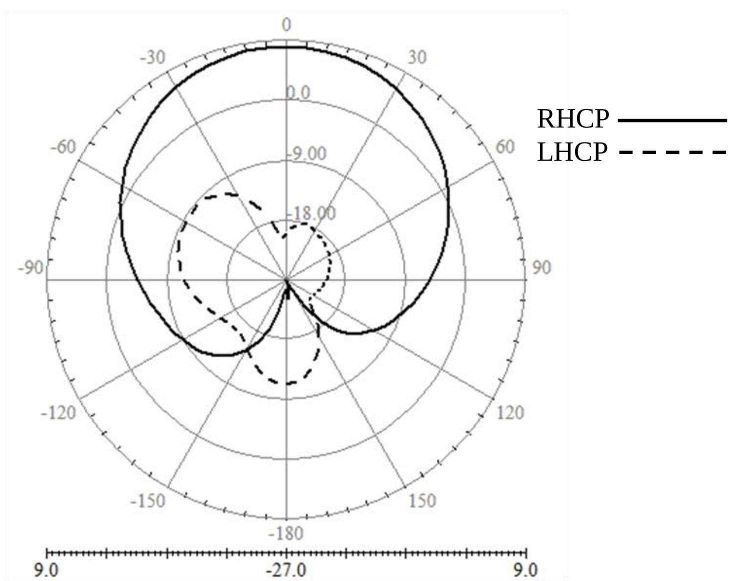


Figure 4-13 H-plane radiation pattern for proximity fed antenna @f_r = 2.4GHz

4.3.3 Aperture feed line

The final design parameters of the antenna fed by aperture feeding shown in Figure 3-20 is simulated by HFSS and verified by CST. Figure 4-14 shows the antenna return loss versus frequency with 10 dB impedance bandwidth is 2.92 %, which is the same as that in the microstrip feeding. Figure 4-15 shows the antenna axial ratio versus frequency with 3 dB axial ratio bandwidth is 0.833 %. The axial ratio bandwidth percentage is the same as microstrip line feeding. The aperture fed antenna yields 7.9 dB directive gain.

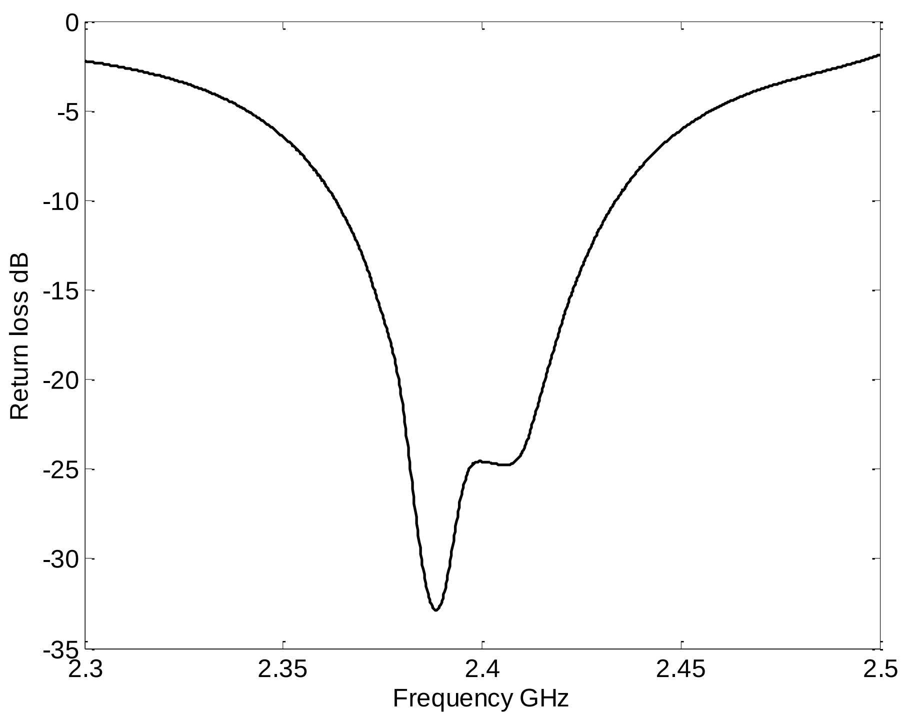


Figure 4-14 Return loss for antenna fed with aperture feeding vs. frequency

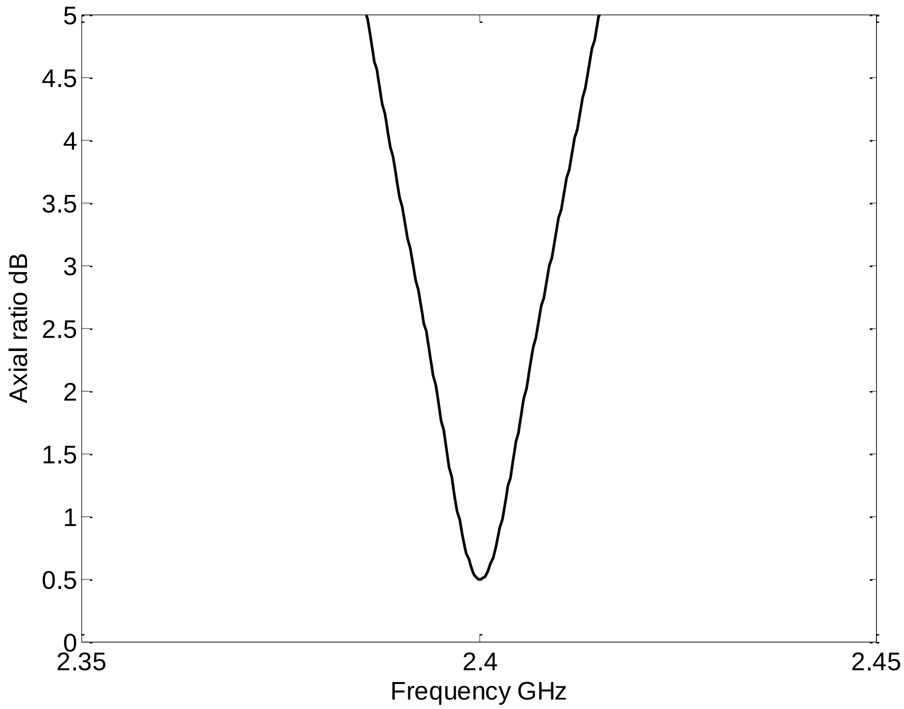


Figure 4-15Axial ratio for antenna fed with aperture feeding vs. frequency

Figure 4-16 and Figure 4-17 show the co and cross-polarization in the E-plane (φ = 0°, 180°) and H-plane (φ = 90°, 270°) respectively using HFSS. The figures show that the antenna is right hand circularly polarized with half power beamwidth ≈ 72.5° in the E-plane and ≈75° in the H-plane. The difference between the co and cross-polarization in both the E and H-planes ≈ 29.9 dB, which is less than that with microstrip feeding but more than that with proximity feeding.

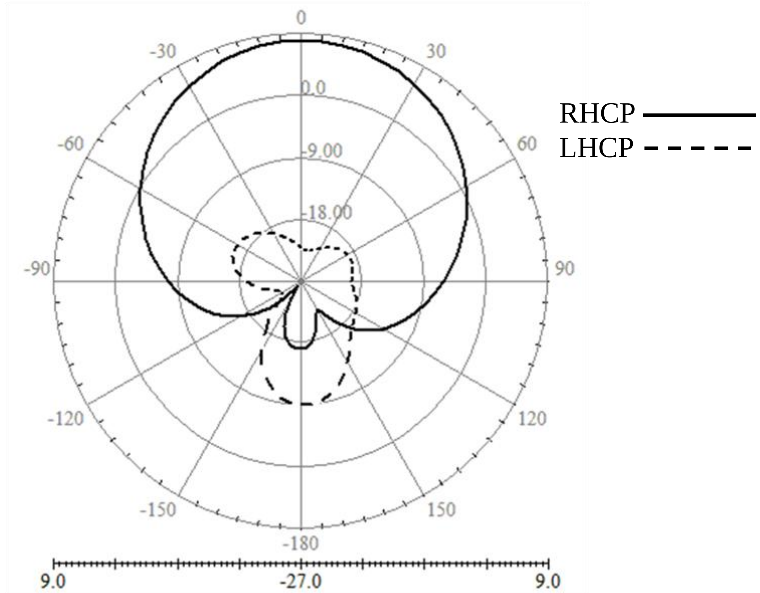


Figure 4-16 E-plane radiation pattern for aperture fed antenna @f_r = 2.4GHz

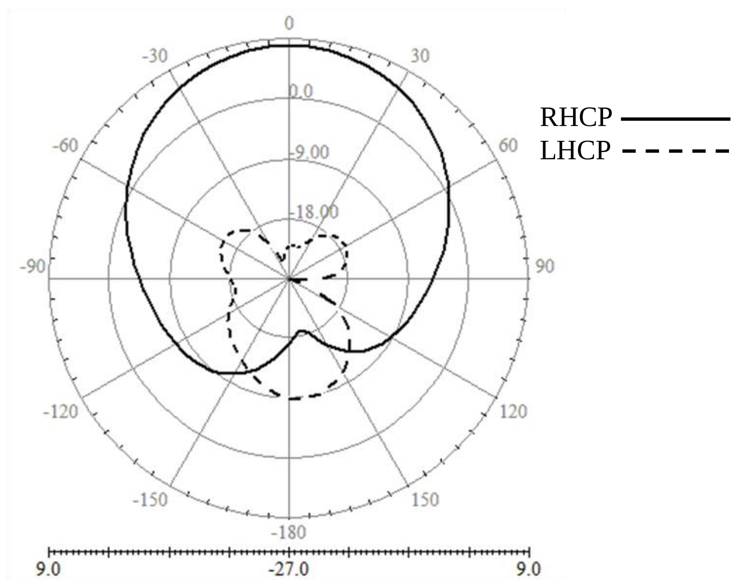


Figure 4-17 H-plane radiation pattern for aperture fed antenna @f_r = 2.4GHz

4.4 Comparison between the 3 antennas

Table 4-1 shows comparison between the 3 antennas in terms of dimensions and radiation characteristics

Point of comparison	Microstrip feed	Proximity feed	Aperture feed
rad mm	23.96	23.3	22.9
d	22.6	21.35	21.6
W_f	4.88	4.62	4.36
Impedance bandwidth %	2.92	5.36	2.92
Axial ratio bandwidth %	0.833	1.45	0.833
Directive antenna gain dB	8.11	8	7.9
Design frequency GHz	2.4	2.4	2.4
Difference between co and cross-polarization in E-plane dB	31.08	28.14	29.9
Difference between co and cross-polarization in H-plane dB	31.08	28.14	29.9
Half power beamwidth in the E-plane °	70	70	72.5
Half power beamwidth in the H-plane	73	77.5	75

Table 4-1 Comparision between the 3 types of single feeding

4.5 Summary

Comparing the results of the actual return loss measured results and the simulation results obtained using HFSS and CST. The measured results and the HFSS results achieve the minimum return loss at the same frequency 2.415 GHz; however the measured results and the CST results follow the same curve shape.

Feeding microstrip antenna with three different types of single feeding techniques affects the antenna output and dimensions.

The microstrip fed antenna is the easiest to model and fabricate. It possesses the largest antenna size compared with the other two antennas to resonate at 2.4 GHz. It has the 10 dB impedance bandwidth as the aperture fed antenna. It has the highest isolation between the co and cross – polarization.

The proximity fed antenna has the largest 10 dB impedance bandwidth and 3 dB axial ratio bandwidth among the two other antennas. The aperture fed antenna is the smallest in size than the other two antennas. It is the hardest to model. It has the same 10 dB return loss and 3 dB axial ratio bandwidth as the microstrip fed antenna. After all simulations and parametric studies were performed, results verifications was done using CST

Table 4-1 shows a comparison between the three single feeding schemes

Chapter 5

Conclusion and future work

5.1 Conclusion

The work presented focused on designing a circularly polarized microstrip antenna operating at 2.4 GHz. The thesis presented a new design based on truncating 2 opposite edges from a circular patch antenna. Three design versions were presented. The first design used microstrip line feeding, the second used proximity feeding and the third used aperture feeding.

Although the microstrip feeding needs a quarter wave length transformers between the antenna and the 50 Ω line feed and it is not easy to match, it is the easiest antenna to model and simulate. Only two parametric studies were performed for choosing the optimum values for the antenna radius and the distance between the antenna center and the perturbation segment. The antenna radius is inversely proportional to the frequency.

The return loss value increases with increasing the distance between the antenna radius and the perturbation segment. Increasing the distance between the patch canter and the perturbation segments get 2 modes closer to each other near the design frequency. The depth of the perturbation segment controls the circular polarization production. It is the largest antenna in size among the other 2 antennas

The proximity feeding doesn't need any matching as it doesn't contact the 50Ω feed line. But it is more complex than the microstrip feeding in modeling and optimization. It requires three parametric studies to determine the optimum values for the antenna radius, perturbation distance and the length of the feed line. The antenna radius is inversely proportional to the frequency. The same effect as microstrip feeding when increasing the perturbation segment distance on getting two modes closer. The length of the feed line affects the antenna return loss and almost has no effect on the axial ratio.

The aperture feeding doesn't need any matching too, but it is the most difficult antenna of the three. It requires four parametric studies for determining the optimum values for antenna radius, the perturbation distance from the patch center, the feed line length and the ground slot radius. Like the other two antennas the antenna radius is inversely proportional to the frequency and with increasing the perturbation distance two modes get closer near the design frequency. The slot dimension affect the circular polarization production, it acts like another perturbation segment. The feed line length affects the antenna return loss value, but doesn't have much effect on the axial ratio value. It is the smallest antenna in size among the other 2 antennas

Feeding the same antenna with three different types of single feeding to radiate at the same frequency; showed some difference in the antenna size and the radiation characteristics.

Results show that microstrip fed antenna yields 8.11 dB directive gain, axial ratio and impedance bandwidth 0.83 % and 2.92 % respectively. The proximity fed antenna yields 8 dB directive gain, axial ratio and impedance bandwidth 1.45 % and 5.36 % respectively. The aperture fed antenna yields 7.92 dB directive gain, axial ratio and impedance bandwidth 0.83 % and 2.92 % respectively.

5.2 Future work

One of the main advantages of a single fed microstrip antenna is that it can be used in the production of antenna array. This work can be extended by investigating the design of an antenna array that uses the antenna presented as its unit element. The future array structure should investigate the use of the 3 feeding techniques presented as well. It should also investigate the arrangement of the array elements.

Another interesting issue is to drive an empirical formula relating the depth of the truncation with the antenna radius and the design frequency.

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