Design & Development of Single Layer Corporate Fed Monopulse Planar Array Antenna

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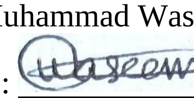
Student Signature: 

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A special acknowledgement to Engr. Noman Ahmad for his scientific creativity, for being a constant source of knowledge, and guiding me throughout my thesis.

Table of Contents

List of Abbreviation

Abbreviation	Definition
DoA	Direction-of-Arrival
AoA	Angle-of-Arrival
RF	Radio Frequency
DF	Direction-Finding
FoV	Field-of-View
SNR	Signal-to-Noise-Ratio

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Abstract

Monopulse antenna systems are employed to determine direction-of-arrival (DoA) where the angle of arrival (AoA) is measured on a single pulse. One of the most significant advantages of this type of system is its speed of operation since all of the necessary computations are performed in the hardware and are instantaneously available. In this thesis, a simple and compact 2x2 microstrip square shaped antenna elements is designed at X-Band which is comprised of only two rat-race couplers as a mono-pulse comparator for tracking radar applications. This system provides sum and difference patterns in both azimuth and elevation planes for the accurate tracking of targets. A circularly polarized antenna is employed for sum pattern to avoid polarization loss among sum and difference patterns. The design is fabricated and the measured results matches the simulation results to great extent. The -10 dB bandwidth of the antennas in azimuth and elevation is 200 MHz and 264 MHz respectively. The sum pattern has gain of 9 dBi in azimuth and elevation at frequency of 10.35 GHz. The null depth in azimuth is -29 dB and -30 dB in elevation with respect to gain of antenna.

Key Words: *Corporate-Feeding, Direction-of-Arrival, Dual-Polarization, Mono-Pulse.*

Chapter 1. INTRODUCTION

This chapter describes the radars and background of monopulse antenna systems and its applications. Moreover, its importance in direction finding techniques and the importance of this method over conventional ways of detection of angle of arrival of targets is also presented.

1.1 Radars

The term Radar stands for Radio Detection and Ranging. It is used for the detection and tracking of targets [1]. Different parameters like exact location, speed and the distance of many kinds of objects are also accurately measured with the use of radars. For this purpose, radar make use of radio frequencies to accomplish the required task. The principle of operations of radars is to send an RF signal towards the target and detect the reflected waves from it. Once the reflected signal is received, various information like distance, velocity or shift in frequency can be extracted by processing that signal.

1.1.1 Components of Radars

The fundamental components used in a radar system are:

- **Transmitter:** It generates and transmit the high frequency and high-power signal to the targeted object through antenna.
- **Antenna:** It is the interface between free space and transmitter. It transmits signals from transmitter towards target and receives back the radio frequency electromagnetic signals from the target.
- **Receiver:** The signals which antenna gets from the target are sent towards receiver for further processing.
- **Signal Processor:** To extract the required information about the desired target the captured signals are given to signal processor part of the radar. The information about the targets may include distance of the target, its size, RCS or how fast the object is changing its position with respect to the radar.
- **Display System:** After the data is being processed, the next step is to present the data in proper readable manner such as numbers or graphs.

1.1.2 Applications of Radars

The following are different radar systems which are used in numerous applications as:

- **Aviation:** For the safety of the travelling in air, the radar systems are used in air traffic

- control, ATC, which checks the motion of aircrafts and avoids the cases of collisions.
- **Military:** One of the major applications of the radar systems are in military. It can be used to detect and track airplanes, flying missiles, military ships, drones etc. It is also used in reconnaissance, surveillance and target acquisition.
- **Weather Forecasting:** The radars used in weather are also called as doppler weather radars. The signals which this radar generates and send are reflected back from the precipitations and moisture in the atmosphere.
- **Navigation:** Radar systems can also be used in marine or terrestrial navigation to find the distance and bearing to landmarks and obstacles.
- **Remote Sensing:** Synthetic aperture radar (SAR) installed on satellites are used to map the terrain, to monitor changes in environment and to detect the objects on surface of earth.

Overall, radar technology provides valuable information for a wide range of applications, contributing to safety, security and scientific research across various domains.

1.1.3 Types of Radars

There are various types of radars designed to suit different purposes and environments. Here are some common types:

- **Primary Radar:** Also known as "Classical Radar" or "Search Radar," primary radar detects objects by sending out radio waves and listening for echoes reflected back from objects. It doesn't rely on any external signal, making it independent of other systems. Primary radar can detect both moving and stationary objects but typically provides less detailed information than secondary radar systems
- **Secondary Radar:** Secondary radar systems, such as the Air Traffic Control Radar Beacon System (ATCRBS) and the Identification Friend or Foe (IFF) system, work by sending out interrogation signals that are answered by transponders on aircraft or other targets. This allows for more detailed information exchange between the radar and the target, including identification codes, altitude, and sometimes even aircraft status.
- **Doppler Radar:** Doppler radar measures the velocity of targets by detecting the frequency shift (Doppler shift) in the radio waves reflected from them. This shift occurs due to the relative motion between the radar and the target. Doppler radar is commonly used in weather forecasting to detect precipitation and in traffic control systems to monitor

vehicle speeds.

- **Synthetic Aperture Radar (SAR):** SAR is a type of radar that creates high-resolution images of the Earth's surface by processing radar signals collected from different positions as the radar platform moves along a path, typically from an aircraft or satellite. SAR can operate in all weather conditions and can penetrate clouds, making it useful for various applications like mapping terrain, monitoring agricultural lands, and detecting changes in land use.
- **Phased Array Radar:** Phased array radar uses multiple antennas and phase shifting to electronically steer the radar beam without physically moving the antenna. This allows for rapid beam scanning, precise control over the direction of the radar beam, and the ability to track multiple targets simultaneously.
- **Tracking Radar:** Tracking radars are specialized radars used to continuously track the position and movement of one or more objects over time. They are commonly used in military applications for targeting missiles, guiding weapons, and tracking aircraft or spacecraft.
- **Monopulse Radar:** Monopulse radar is a type of radar that uses multiple antennas to accurately measure the direction of a target. It compares the phase or amplitude differences between signals received by these antennas to determine the angle of arrival of the target.

These are just a few examples of the many types of radars that exist, each tailored to specific applications and operating environments.

1.2 Monopulse Antenna System

Monopulse antenna systems are widely used in radar and communication systems for tracking and guidance purposes. This kind of systems gives accurate angular information of incoming signals, making them essential for applications such as target tracking, missile guidance, and navigation.

Monopulse antennas are used extensively in radar applications for tracking and searching of targets. These antennas extract information of a target using a single pulse. The sum and difference patterns generated by these antennas makes it possible to track a target with greater precision and accuracy [1]. They are designed from the combination of radiation structures and feed networks working as comparator. Different monopulse antennas uses complicated radiation structures like parabolic shaped antennas. The feeding networks are based on slotted waveguides or substrate integrated waveguides which makes the systems bulky and costly. Nonetheless, microstrip antenna is the best solution because of its compactness, low cost, and simple geometry.

1.2.1 Basic Principles

Monopulse antennas work on the principle of comparing the phase or amplitude of signals received from different spatial regions to determine the angle of arrival of the incoming signal. Unlike conventional antennas that provide only amplitude information, monopulse antennas exploit the phase differences between received signals to achieve higher angular resolution.

1.2.2 Components

A monopulse antenna system typically consists of multiple antenna elements arranged in a specific configuration, along with signal processing circuitry. The antenna elements are often arranged to form a sum and difference pattern, allowing the system to measure the angular deviation of incoming signals with respect to a reference axis

1.2.3 Sum and difference patterns

Monopulse antennas generate two main radiation lobes - a sum lobe and a difference lobe. The sum lobe represents the total power received by the antenna array, while the difference lobe provides information about the phase or amplitude difference between signals received by different elements of the array as shown in Fig 1-1.

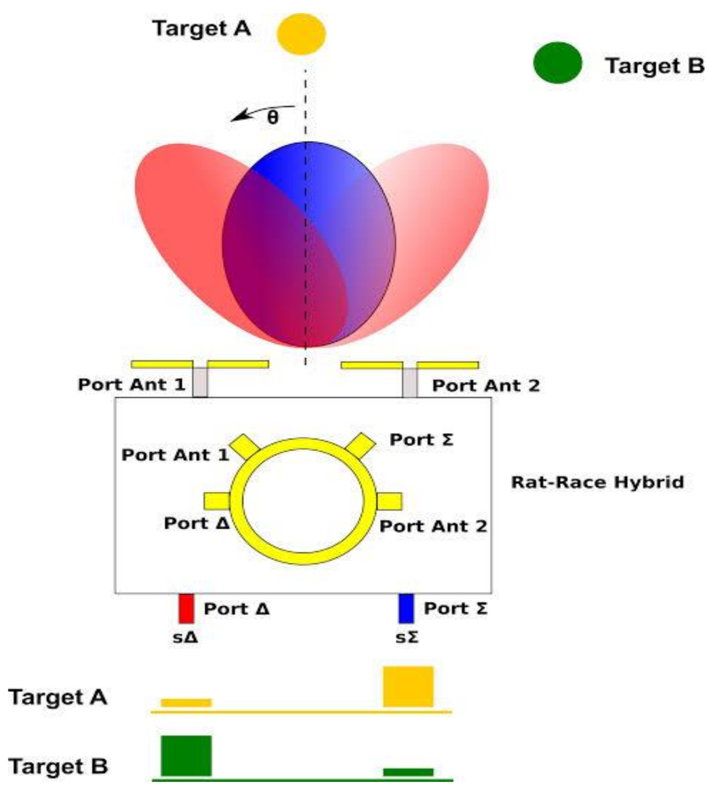


Figure 1-1: Monopulse antenna system concept [2]

1.2.4 Tracking Mechanism

Monopulse systems use the information from the sum and difference patterns to derive error signals that indicate the deviation of the received signal from the desired direction. These error signals are then used to steer or adjust the orientation of the antenna array, thereby keeping the antenna pointed accurately towards the target or desired direction.

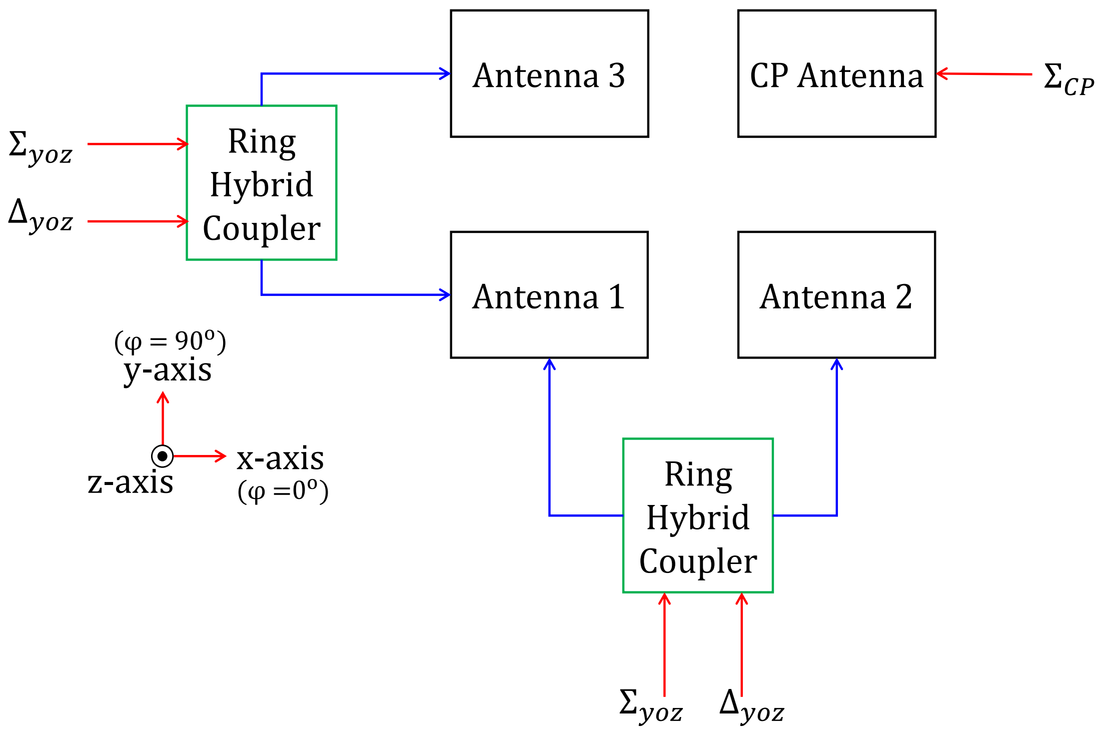


Figure 1-2: Configuration of the proposed monopulse antenna system

Fig 1-2 shows the configuration of the proposed monopulse array antenna. The antenna array is co-polarized in both axes, with very lower cross polarization when used for vertical or horizontal axis. The operation of frequency is in lower x-band. All of the antenna elements are corporate-fed with the interspacing electrical distance of 90 degrees. The design of this planner patch array is single layer which reduces the complexity in fabrications. The proposed design use only two rat-trace couplers for the use of comparator function which is simpler structure than the conventional designs of comparators using corporate feeding for the antenna array elements and number of rat-trace couplers. The antenna system works well both in transmission and reception as the sum and difference patterns are made in horizontal and vertical axis. This monopulse antenna system also uses circularly polarized antenna elements which adds an advantage of receiving electromagnetic waves in dual polarization.

1.3 Applications

Monopulse antenna system are used in the radars applications for the accurate determination of direction of arrival of targets. It is also used to reduce the jamming. It decreases many problems which are faced by conventional conical scanning radars. The antenna system has also extensively used by different satellite as shown in the following figure.

- **Radar Systems:** Monopulse antennas are extensively used in radar systems for target tracking, missile guidance, and navigation. Their high angular accuracy and fast response make them suitable for tracking moving targets with precision.
- **Satellite Communication:** Monopulse antennas are also used in satellite communication systems for tracking satellites and maintaining the alignment of ground-based antennas with the satellite's position.
- **Aircraft Navigation:** In aviation, monopulse antennas are employed in systems such as Instrument Landing Systems (ILS) and Traffic Collision Avoidance Systems (TCAS) for accurate angle measurements and guidance as shown in Fig. 1-3.

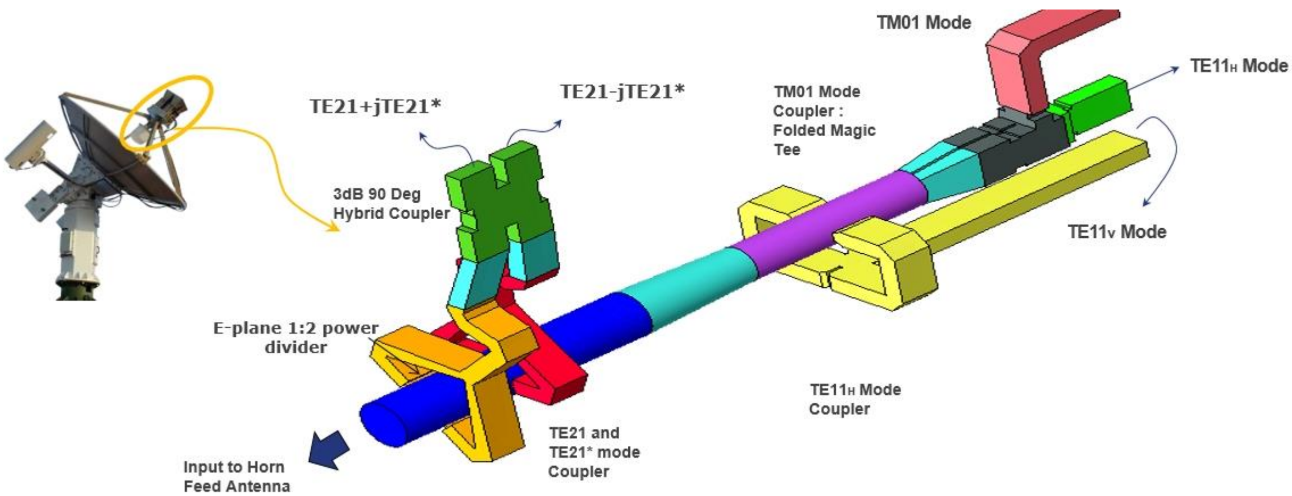


Figure 1-3: Monopulse antenna system for satellite tracking [3]

1.4 Advantages

The following are some of the advantages of monopulse antenna systems over convention methods of tracking in radars.

- Angular accuracy
- Fast response time
- Robustness against noise and interference
- Suitable for tracking moving targets

1.5 Challenges

Overall, monopulse antenna systems play a crucial role in various applications where accurate angular measurements are essential for tracking, guidance, and navigation purposes. Their effectiveness lies in their ability to provide precise directional information even in challenging environments.

- Complex signal processing requirements
- Design and calibration considerations for achieving desired performance
- Cost and size constraints, particularly for portable or mobile applications

1.6 Problem Statement

The primary objective of this project is to design, simulate, and optimize a monopulse antenna system for radar applications with the following key goals:

- **Direction Finding Accuracy:** Achieve high accuracy in determining the direction of incoming signals, minimizing errors and ambiguities in angle estimation.
- **Tracking Capability:** Develop the ability to track multiple targets simultaneously with high precision and reliability.
- **Robustness to Environmental Factors:** Design the antenna system to be resilient to environmental factors such as changes in weather conditions, terrain, and electromagnetic.
- **Compactness and Portability:** Ensure the antenna system is compact, lightweight, and portable without compromising performance, making it suitable for mobile radar applications.

1.7 Thesis Objectives

The following key points explains the main objectives for the proposed design**:**

1. Design of monopulse antenna system for direction finding applications in radars.
2. To bring the comparator and radiation part of the monopulse antenna systems to single layer.
3. To reduce the complexities of the comparator part of the monopulse antenna system for direction finding applications.
4. To reduce the number of couplers used in conventional designs for monopulse antenna system.
5. To get sum and difference patterns in azimuth and elevation for the angle of arrival.
6. To add circularly polarized antenna for receiving electromagnetic waves in dual axis.

Chapter 2. LITERATURE REVIEW

Monopulse techniques have been used in literature using different antenna structures and monopulse comparators for the accurate detection of angle of arrival (AoA) mainly in the field of radars. These systems can be used in the applications of radars where the targets need to be detected in faster speeds in accurate manner. Monopulse system can find a target by sending a single pulse towards it and extracting the information using the reflected pulse. Various methods and designs have been used from [4] – [9] to realize monopulse antenna systems.

In [4] a 2x1 microstrip based antenna is made at 10 GHz comprising of four rat-race couplers as a comparator part. Although, the antenna is well matched and it has a high null-depths but the design is based on two layers making it more complex than single layer antenna designs. Hybrid couplers are used with the four patch antenna elements to make a monopulse comparator. The feed is very complex as it consists of four rat-trace couplers in the feed. The antenna array system is based on the multilayer configuration. These antennas can make sum and difference patterns in two planes which are orthogonal to each other. A via-fed method of feeding is used under the microstrip patch elements to eliminate the mutual coupling in the antennas and feeds as shown in the following figure.

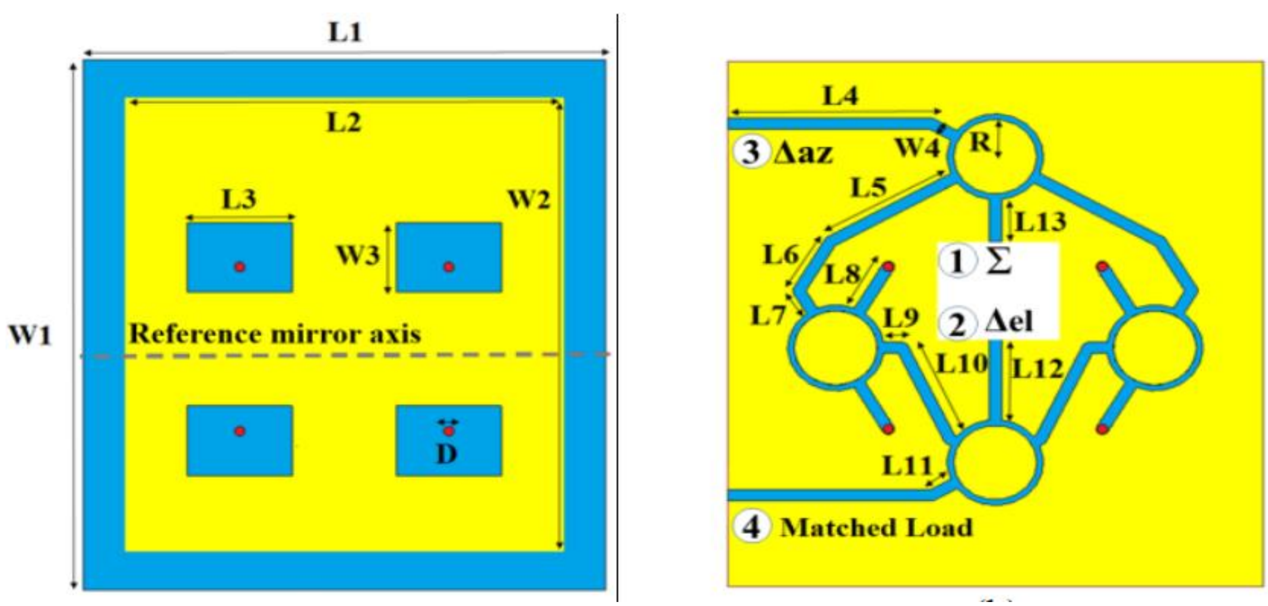


Figure 2-1: Monopulse antenna system [4]

The work in [5] shows a 4×4 microstrip antenna array designed for monopulse tracking which uses four rat-trace couplers at the lower substrate. The design is made and simulated in IE3D software. Different feeding techniques have been used for the radiating part of antenna. This design has improved -10 dB bandwidth of 13.9 % around 9 GHz. The maximum gain of the antenna array is 24.7 dBi which covers the complete band. The null depth is around less than 30 dB with side lobes lower than -15 dB. The beam of the antenna is very narrowed with beamwidth of only 9.0 degrees. This antenna array shows applications for estimation of target in radars. The design possesses comparatively larger bandwidth than other monopulse antennas in the literature. Also, the radiating part of the antenna systems is fed with mixed signals so that to improve the cross polarization of the antenna. The rat-trace coupler is also used due to which the antenna array can be made to work as transmitter as well as receiver. the problem in this design is its complexity and multilayer structure, as the antenna elements are excited using coupling.

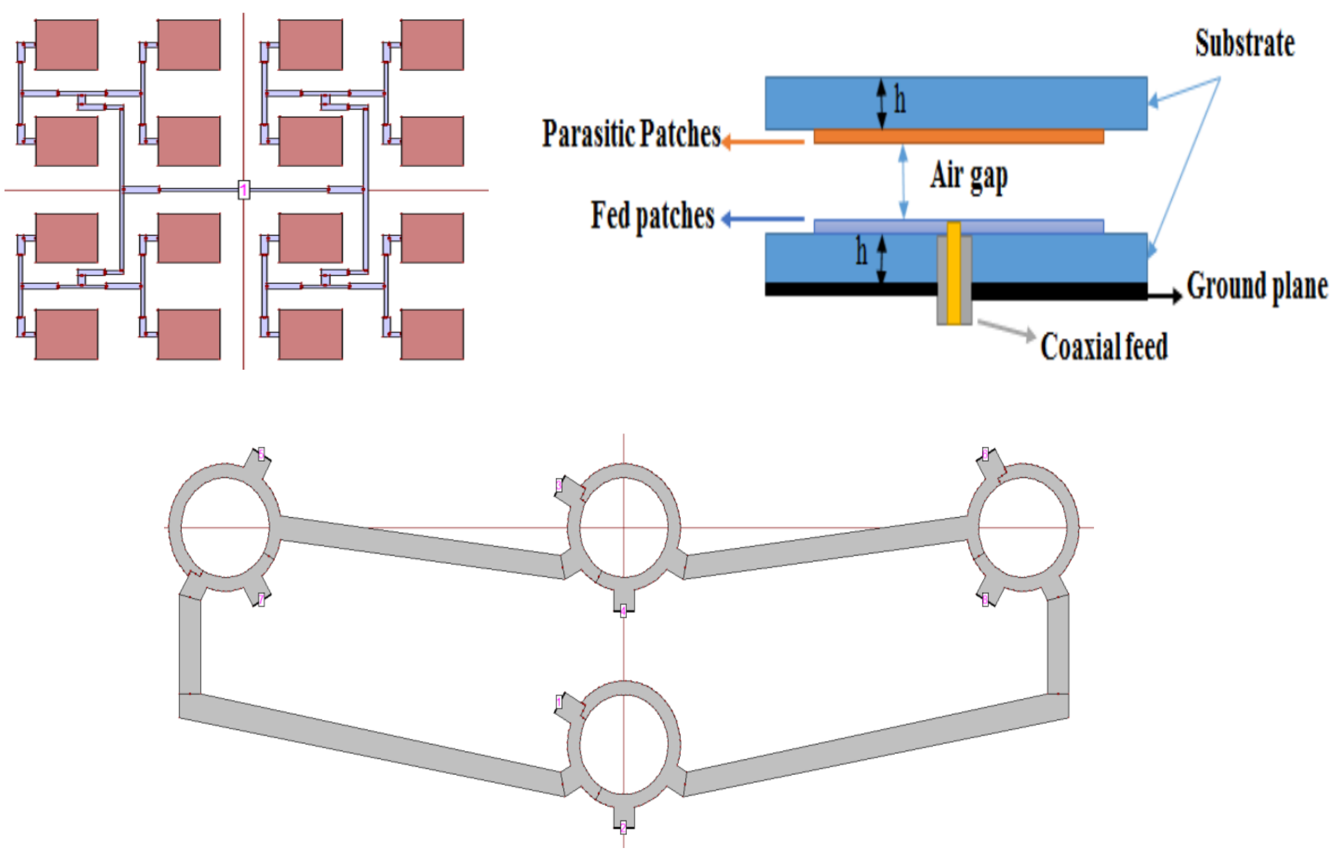


Figure 2-2: Antenna array with four rat-race couplers as comparator [5]

The work reported in [6] shows a single layer structure for monopulse antenna system where the radiation network and comparator part of the system lies on the single plane. This antenna system operates in frequency range from (13.85 – 15.1) GHz with center frequency of 14.25 GHz and -10 dB bandwidth of 5.6 %. Due to the microstrip antenna array the overall gain is around 24 dBi. The difference pattern resulting from the array has a null depth of -30 dB. The sum pattern shows less than -17 dB sidelobes. Instead of rat-race couples as comparator part, here 90^{o} couplers have been used.

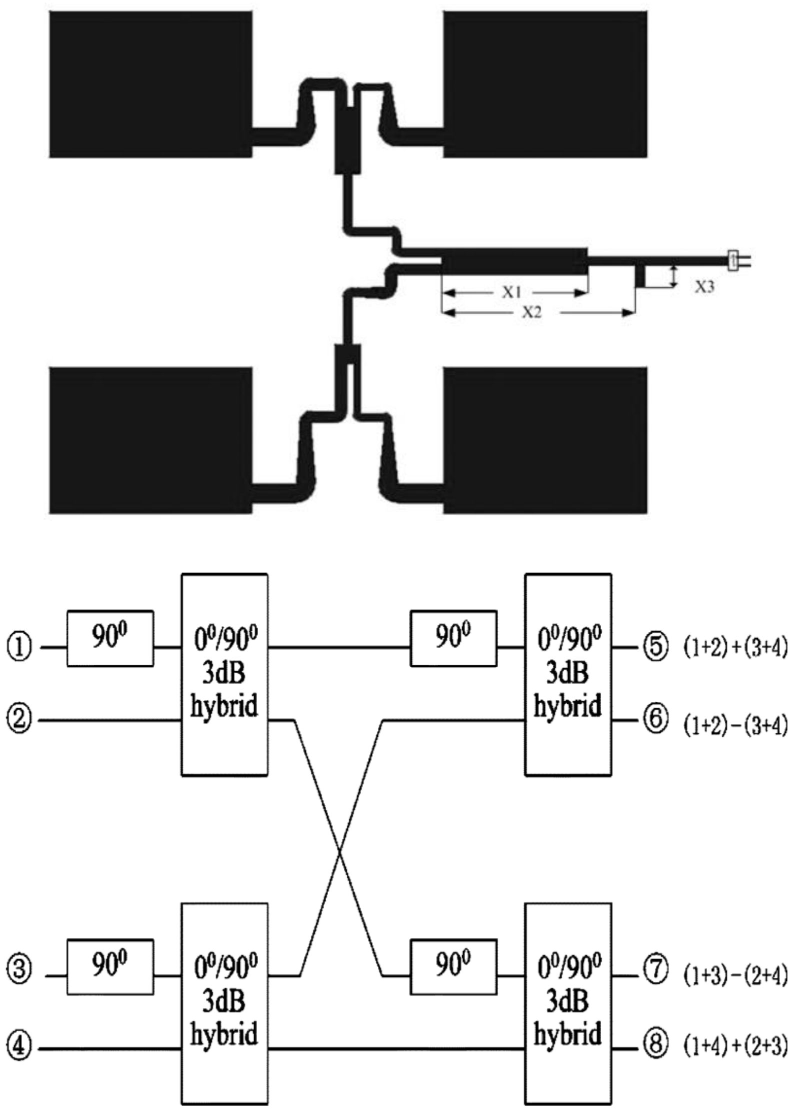


Figure 2-3: Monopulse antenna, upper side: Radiator part, lower side: comparator part [6]

Dual probe fed microstrip antenna is designed in [7] which has impedance bandwidth of 345 MHz center frequency of 2.3 GHz in the band from (2.12 – 2.45) GHz. The isolation is measured which is greater than -15 dB in the whole mention band. As the it is only a single element antenna with combined with coupler, the overall size of the antenna is very less compared to the designs for monopulse antenna system in literature. Though the structure is very simple but this antenna provides sum and difference patterns in a single plane. The radiating part consists of slotted patch with dual feeds from the hybrid 180^{o} coupler.

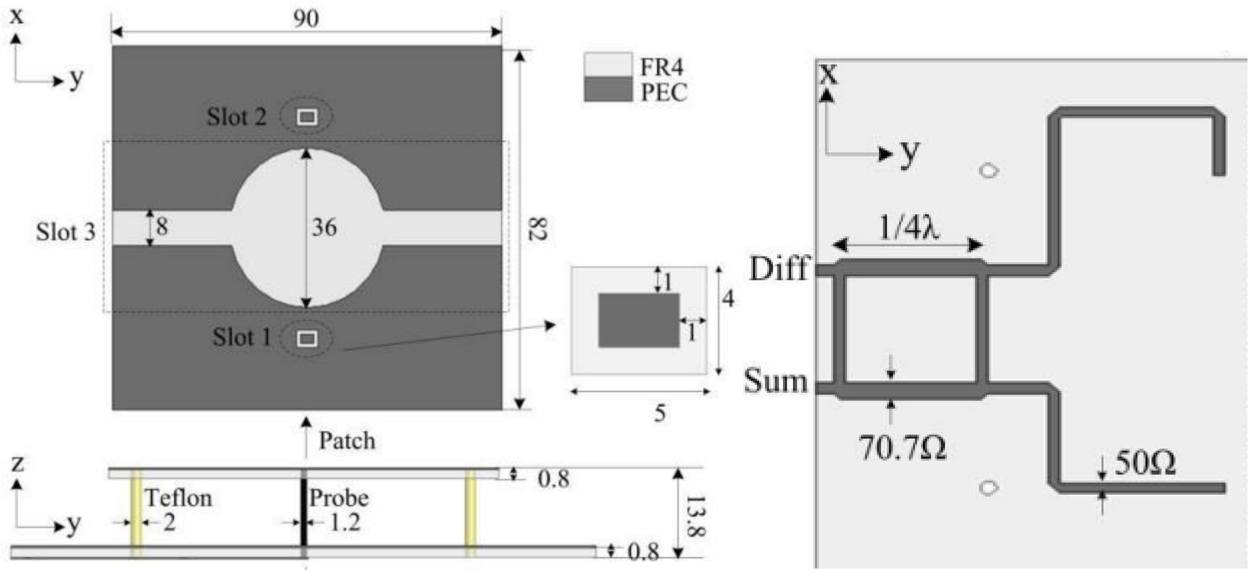


Figure 2-4: Single element slotted patch antenna with hybrid 180^{o} coupler [7]

Another antenna system is proposed in [8] which uses the series feeding technique. The antenna operates at the frequency in Ka-band. This system can only work in one axis as the antenna elements are made in one-line series. There is only one rat-trace coupler used in this work to find the patterns of sum and difference for the angle of arrival (AoA) information. The difference pattern has a very nice null of almost -30 dB. The return loss measured for both sum and difference port are lower than -10 dB. This work shows many applications in tracking radars and collision avoidance systems.

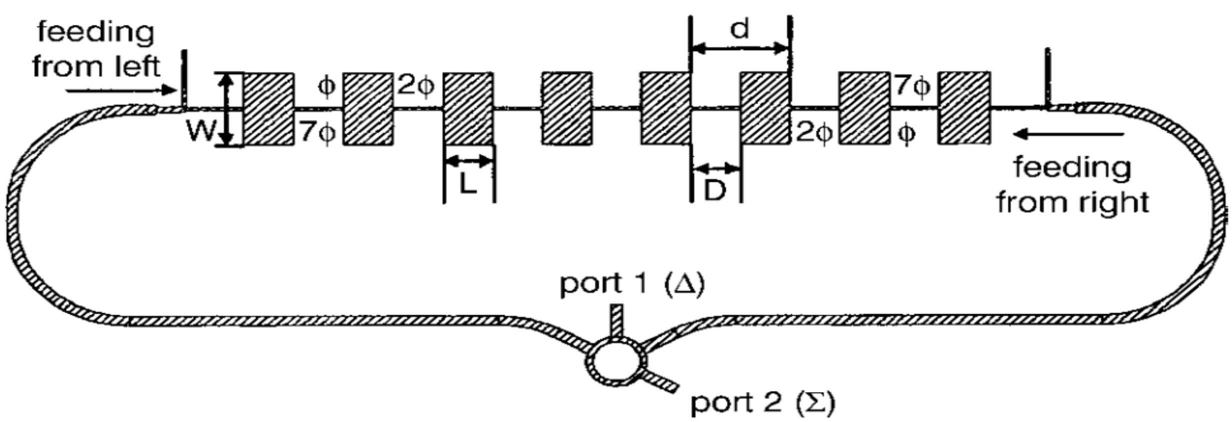


Figure 2-5: Single axis monopulse antenna system [8]

In [9] an array of 4×4 antenna elements are designed fed by couplers. This antenna system operates in C-band. Th antenna system has a wide band monopulse comparator with -10 dB impedance bandwidth of 28.2 %. The depth of the null is -28 dB from (5 – 6.7) GHz. It has also high gain of approximately equal or greater than 18 dB. This system can be used in many applications like tracking radars according to its measured results.

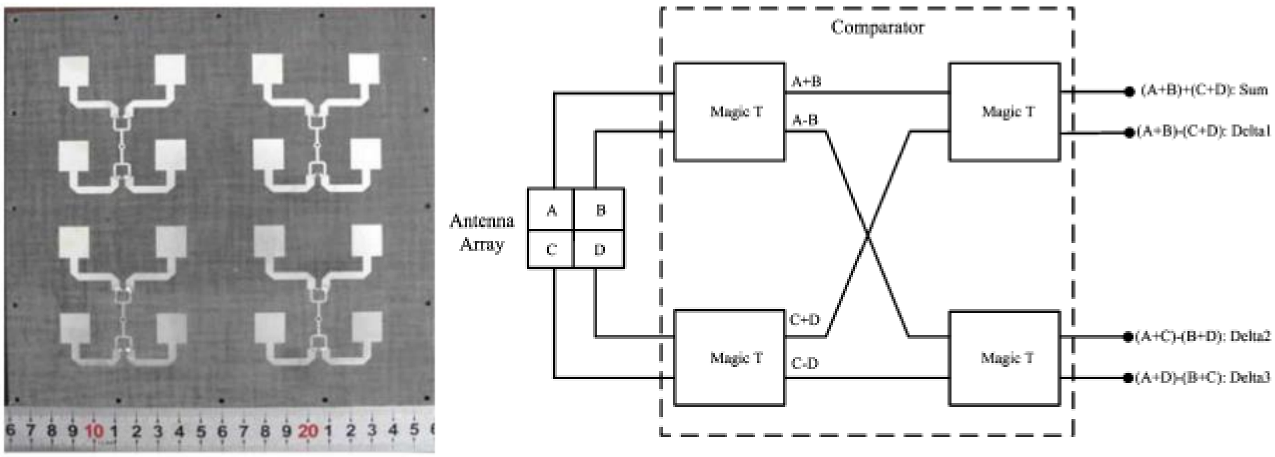
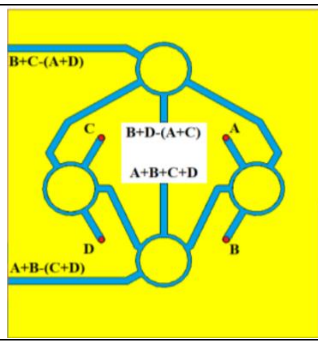
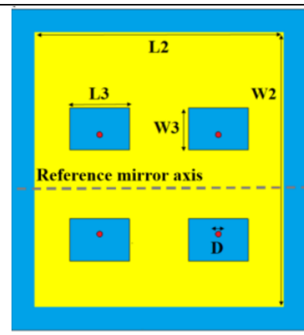
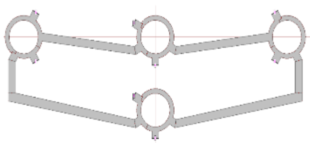
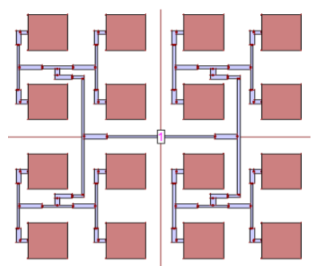
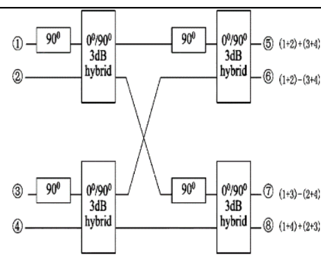
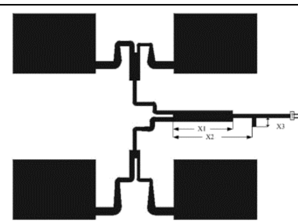
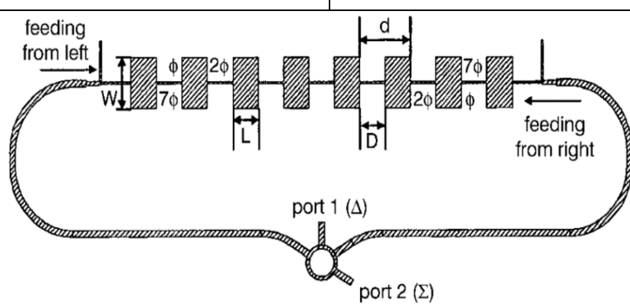
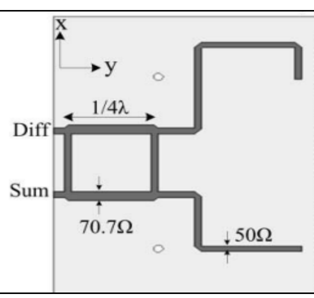
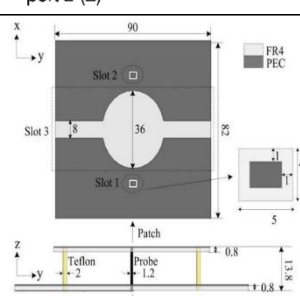
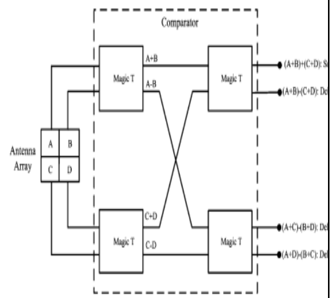
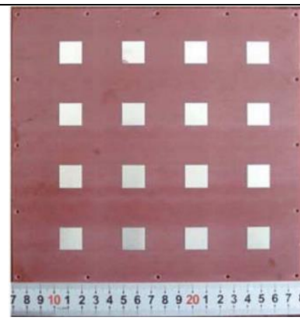


Figure 2-6: Left: Fabricated antenna array, right: monopulse antenna system [9]

Almost many of the designs in the literature is based on large number of rat-trace coupler and power dividers, as a result of which many designs are based on multilayer configurations.

Table 2-1: Table of literature review

Paper	Design (Comparator Part)	Design (Radiator Part)	Frequency Band	No. of layers	Null depths
[4] Compact Via-Coupling Fed Monopulse Antenna with Orthogonal Tracking Capability in Radiation Pattern			9 – 11 GHz	2	Azimuth = -20 dB & Elevation = -24 dB
[5] Microstrip Antenna Array with Rat-race Comparator at X-Band for Monopulse Tracking Radar			BW of 13.9 % around 9 GHz	2	Better than -30 dB
[6] A Compact Single Layer Monopulse Microstrip Antenna Array			13.85 – 15.1 GHz, BW = 5.6 %	2	Less than -30 dB
[7] Low-cost monopulse antenna using bi-directionally-fed microstrip patch array			Ka- Band	1	-30 dB
[8] Single Patch Antenna with Monopulse Patterns			2.11 – 2.45 GHz	1	-32.7 dBi

[9] A Broadband Planar Monopulse Antenna Array of C-Band			5.05 – 6.67 GHz	2	-28 dB

2.1 Summary of literature review

Various methods and designs have been used from [4]-[9] to realize monopulse antenna systems. In [4] a 2x1 microstrip based antenna is made at 10 GHz comprising of four rat-race couplers as a comparator part. Although, the antenna is well matched and it has a high null-depths but the design is based on two layers making it more complex than single layer antenna designs. [5] shows a 4x4 microstrip array design for monopulse tracking which uses four rat-trace couplers at the lower substrate. This design has improved bandwidth of 13.9 % around 9 GHz. The work in [6] shows the 2x2 array with a complex comparator network on a single layer around 14 GHz. [7] shows antenna design in one axis for Ka-band which can find AoA in azimuth only. Dual probe fed microstrip antenna is designed in [8] which has impedance bandwidth of 345 MHz around 2.3 GHz. Though the structure is very simple but this antenna provides sum and difference patterns in a single plane. The work reported in [9] shows C-band antenna array in combination with magic T-junction as comparator network. Here the main focus is on the design of wide impedance band of 28.2 % of monopulse antenna array.

In this work, new mechanism for obtaining the monopulse function is used. The antenna system uses the 2x2 elements for sum and difference in azimuth plane. It also uses orthogonal feeds to one of square antenna for sum and difference patterns in elevation. The whole structure uses only two rat-trace couplers for the monopulse comparator which is not done in literature. The overall design is made on a single layer. All the required phase shifts are achieved using the additional electrical length of microstrip lines, which functions like phase shifter. This system can be used in applications where compactness of the designs is required.

Chapter 3. DESIGN METHODOLOGY

The design process of the proposed co-polarized differential fed monopulse antenna follows various steps. As the initial step simple patch antenna is matched at X-band where length of the patch is different than its width. Such kind of microstrip patch antennas is easy to matched at any frequencies as the input impedance of the patch is easily controllable with changing length and width of the patch. Different techniques can be used to match the patch to 50 ohms impedance line which includes matching through inset feed and the common method of the use of quarter wave transformers at specific frequency. When microstrip antennas are made at higher frequencies, the dimensions go to millimeters (mm) or sometimes micrometers (um) depending upon frequency of operation. As a result, the fabrication limitations should be kept in considerations, as different PCB manufacturers has their own specifications.

The rectangular patches can be easily made to produce less impedance at the input of the patch. To matched such rectangular patch antennas, impedance needed from quarter wave transformer is less, so the required width is more, which is easily to fabricate. In the case of square shaped patch antennas, the input impedance is very high at high frequencies. As by changing the width, the length should also be changed at the same proportion, so the input impedance also remains the same. As a result, the required width of a quarter wave transformer is required to produce high impedance, with very narrower widths. So, it’s not very easy to match the square width patch antenna with quarter wave transformer whose width should be such that it can easily be fabricated with normal PCB manufacturers.

In this design, initially the matching is performed with quarter wave transformer with rectangular patch antenna. The calculated length and width at X-band of quarter wave transformers were such that they can be easily fabricated. According to the target of this thesis, the shape of the microstrip square antenna is chosen to be square as every element should be fed with multiple feeds, so from every side same feed can used for matching because of the symmetric structure. Next design is of the square patch antenna with addition of orthogonal feed to main feed. The surface current distribution on the patch due to main feed is vertical due to which its vertically polarized. The current distribution due to the feed which is orthogonal to the main feed is in horizontal direction. This technique makes the antenna linearly polarized in dual axis.

3.1 Square Shaped Single-Fed Antenna

As the starting point of the design, single fed square shaped antenna is designed. The design frequency is in X-band. The dimensions of a single antenna element 9x9 mm. As mentioned before, the patch is matched to 50 ohms line using quarter wave transformer. The calculated width of the quarter wave transformer is 0.18 mm according to design frequency. This width is very small and almost impractical according to the available PCB manufacturing facilities, so optimization of the width and length is dome in such a way that at least the minimum width should of 0.2 mm.

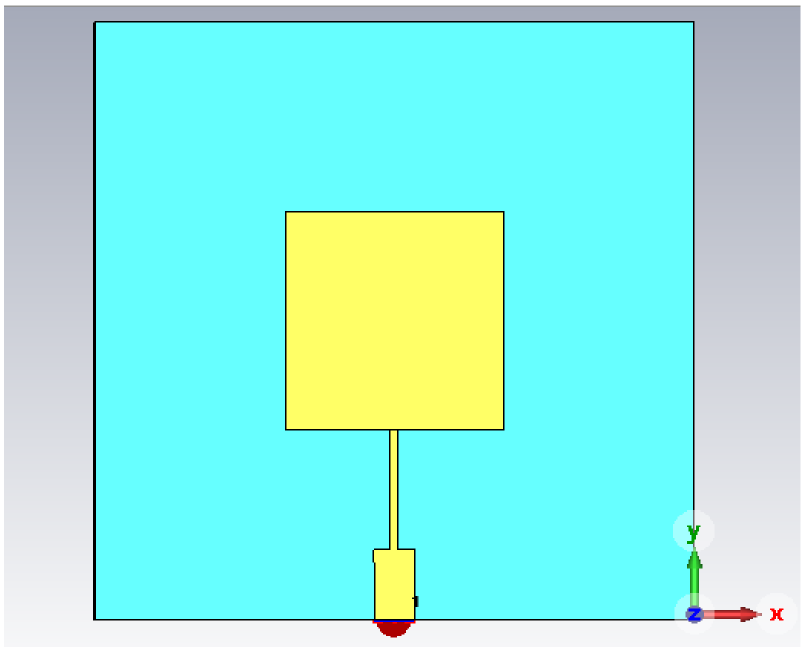


Figure 3-1: Single Fed square shaped antenna

In the Fig. 3-2 the S-parameters are shown for the square shaped patch antenna. The antenna resonates at around 8.3 GHz, which in X-band. The calculated width for the quarter wave transformer is 0.18 mm, for which the antenna resonates very well but due to its very small width, the square antenna cannot be finalized with this width of quarter wave transformer from fabrication point of view. So, in the design it has been optimized to 0.2 mm which is comparatively is easy to fabricate. As changing width can produce mismatches at the design frequency, so the length of quarte wave transformer can be varied as it directly influences the resonating frequency because every value of length of quarter wave transformer corresponds to certain specific frequency.

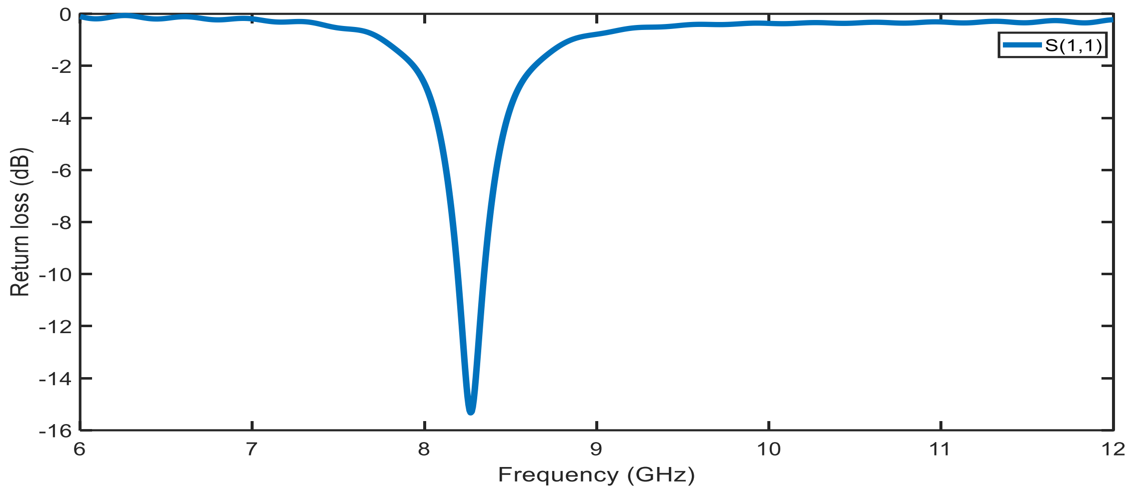


Figure 3-2: Single Fed square shaped antenna

3.2 Square Shaped Dual-Fed Antenna

The 2nd step in the design of monopulse antenna system is to make a square shaped dual-fed antennas with orthogonal feeds which is used in both designs presented in this thesis as shown in Fig. 3-3. The first feed is the main feed in the x-axis which will result in making the antennas as vertically linear polarized. The second feed is orthogonal to the main feed as shown in the following figure. This orthogonal feed makes the antenna as horizontally linear polarized. In this way this antenna can be made dual polarized. The width and length of the quarter wave transformer of the orthogonal feed id same as that of main axis because of the symmetrical structure of the square shaped patch antenna.

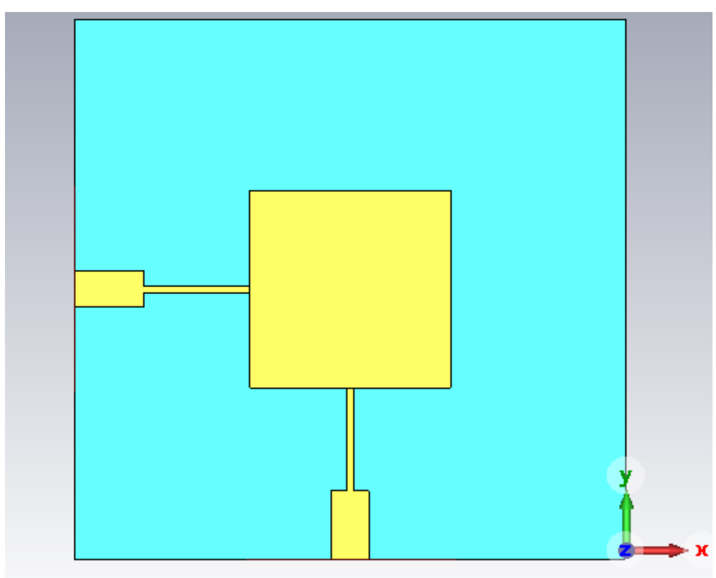


Figure 3-3: Dual-Fed square shaped antenna

The plot of the S-parameters below shows S11 and S22 results for the above designed dual-fed antenna in Fig. 3-4. The antenna resonates at 8.35 GHz. As square shape of the antenna is symmetrical from every side, so both of the ports exactly show same return loss of almost -15 dB.

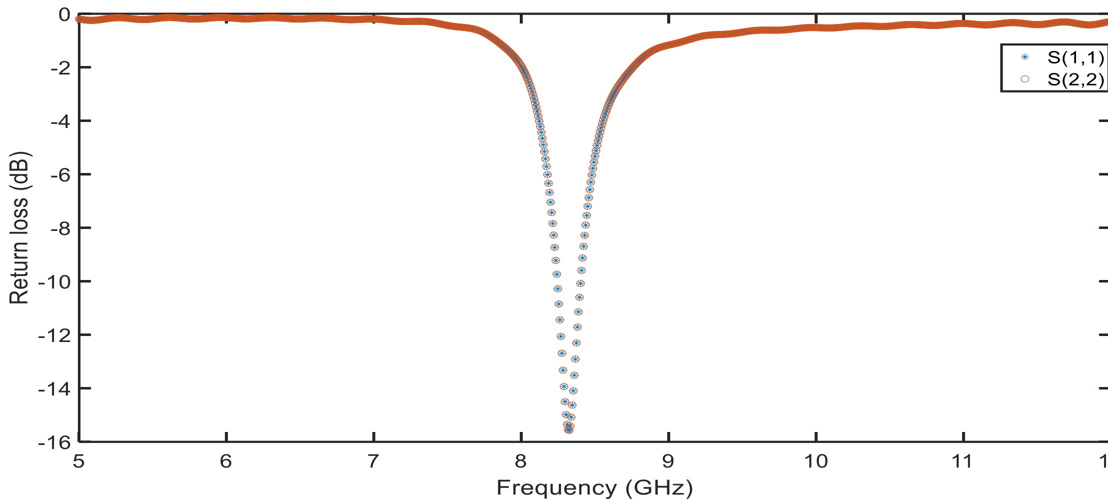


Figure 3-4: S-parameters of the dual fed square antenna

The Fig. 3-5 shows the direction of current density which is resulted from port 1. At this time of port 1 excitation, the current density due to port in not there, because port 2 is not simultaneously excited along with port 1. Port 2 for now is terminated with 50 ohms. The direction of current density shows the vertical polarization as in the previous case of single-fed antenna.

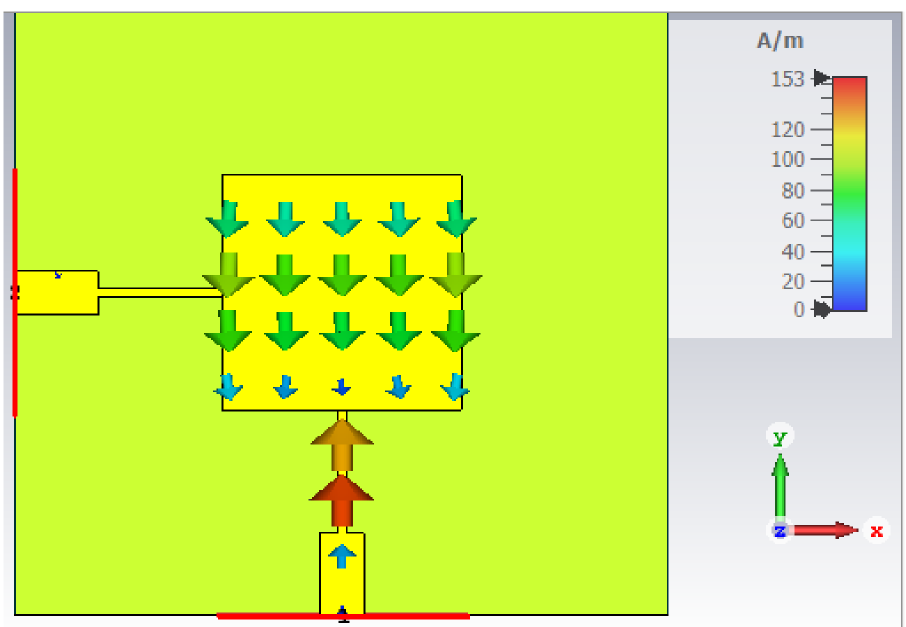


Figure 3-5: Direction of current density due to port 1

After checking polarization of antenna due to port 1, now the surface current due to port 2 can be analyzed. Fig. 3-6 shows these results of surface currents. As expected, the direction of current density is in x-axis, which means the electric field has only x component, and the antenna is horizontally polarized. In this way, the antenna can be made dual polarized due to orthogonal feed added to main feed.

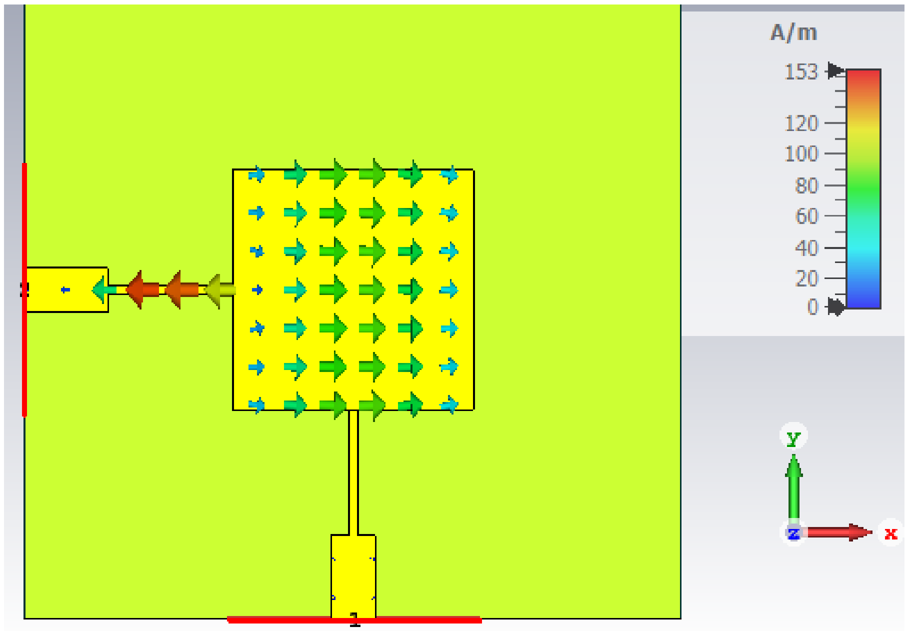


Figure 3-6: Direction of current density due to port 2

3.3 Differential-Fed Design of 2x2 Patch Monopulse Antenna Array

The Differential-Fed design for the radiating part is the 2x2 patch array antenna. This antenna is supposed to generate sum and difference patterns for both azimuth and elevation plane. The sum and difference plane should be around zero degrees. The design parameters of the proposed patch array antenna are shown in table 3-1.

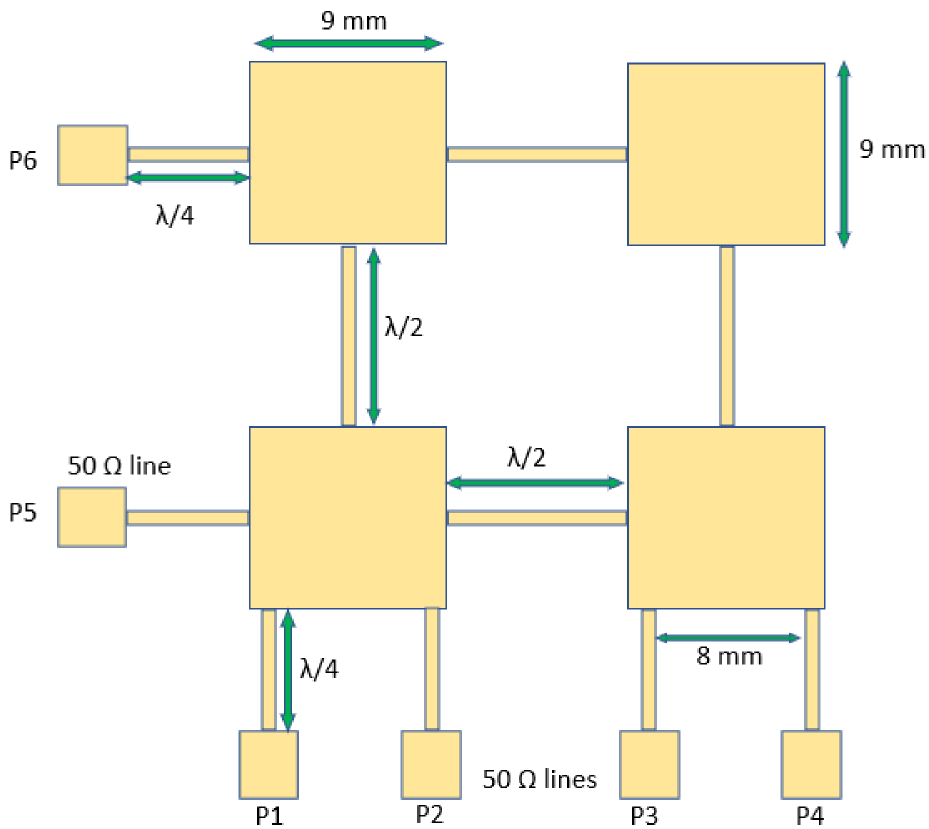


Figure 3-7: 2x2 patch array monopulse antenna with dimensions

The following table shows the design parameters of the 2x2 antenna array as shown in Fig. 3-7.

Table 3-1: Design parameters of the monopulse patch array antenna

S.no	Parameter	Value (mm)
01	Square patch dimensions (LxW)	9×9
02	Interspacing between patches (Horizontal)	4.54 + 4.54
03	Interspacing between patches (Vertical)	4.54 + 4.54
04	Differential feeds center to center distance	8
05	Quarter wave transformer, widths	0.3
06	Quarter wave transformer, lengths	4.54

The design is made according to the mentioned parameters. Total of 6 ports are required for the array. Four ports are used to excite the array in x-axis as shown in the figure. The patterns result from these will determine the angle of arrival in azimuth plane. Two ports are used to excite the array in the y-axis. The sum and difference patterns resulting from these ports will be in elevation plane. This information is enough to be put in the equation of monopulse function to find the angle of arrival.

3.3.1 Sum and difference patterns in Azimuth

Starting from the sum pattern in azimuth plane, as shown in Fig. 3-8. The results are displayed in different view for better visualization. This 2D pattern can better explain this pattern at for fixed phi (zero degrees). The angle of the main lobe is 1 degree, which is very close to zero degrees. The side lobe levels are -23.1 dB which is very good for this pattern. The sum pattern is obtained by simultaneously exciting port1, port2, port3 and port 4. All of the ports have zero degrees phase difference due to which it results in sum pattern. Following is the resulting difference pattern in azimuth plane. The null can be seen at 1 degree with magnitude of -15 dB which is better for the overall performance. The side lobe levels are 0.5 dB. The difference pattern is obtained by simultaneously exciting port1, port2, port3 and port 4. All of the ports have 180 degrees phase difference due to which it results in difference pattern.

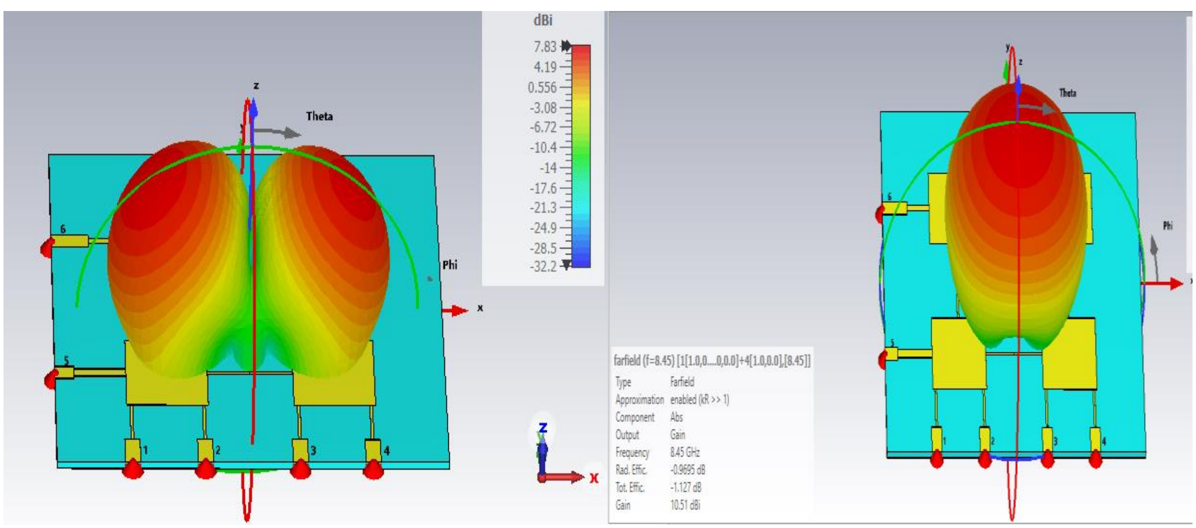


Figure 3-8: Far field Gain Abs, Phi=0 (3D Sum and difference patterns in azimuth plane)

3.3.2 Sum and difference patterns in Elevation

The following results in Fig. 3-9 shows sum pattern in elevation plane. The maxima can be seen at 5 degrees with magnitude of 10.2 dBi which is in the acceptable range for monopulse antenna system. The side lobe levels are -21.7 dB. The sum pattern in elevation plane is obtained by simultaneously exciting port5 and port6. Both of the ports have zero degrees phase difference due to which it results in sum pattern. Below are the results for pattern in elevation plane. The null is at 3 degrees with magnitude of 10 dBi which is in the acceptable for monopulse system. The side lobe levels are -1.1 dB. The difference pattern in elevation plane is obtained by simultaneously exciting port5 and port6. Both of the ports have 180 degrees phase difference due to which it results in difference pattern.

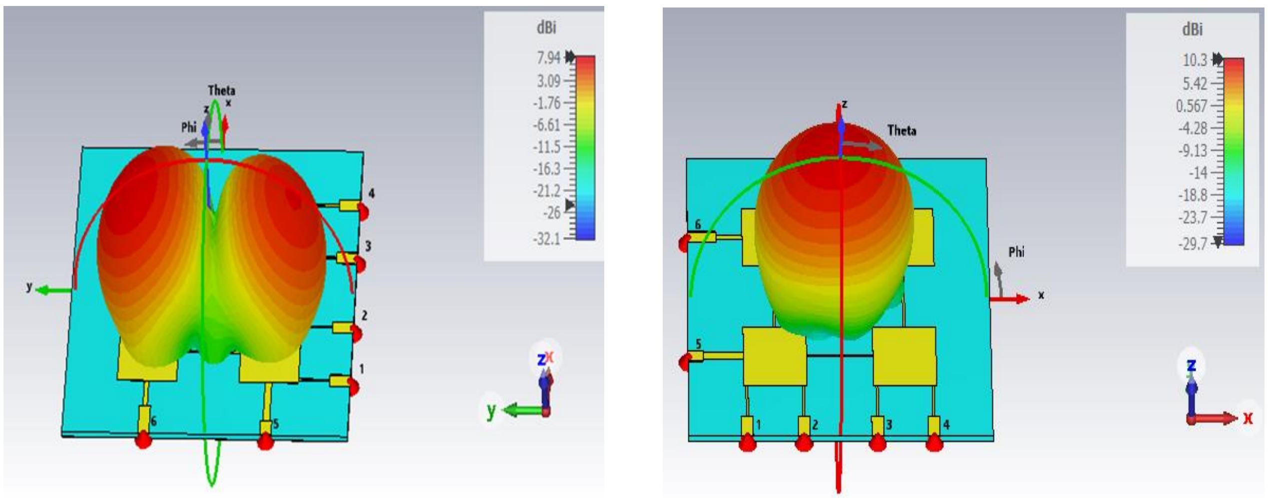


Figure 3-9: Far field Gain Abs, Phi=90 (3D Sum and difference patterns in elevation plane)

3.3.3 Drawbacks of the Differential-Fed monopulse antenna system

The 1st design is based on the differential fed antennas which has certain pros and cons. The only advantage is to minimize spurious feeds radiations of the closely spaced antenna elements. Overall, the geometry is complex and it is difficult to match the antenna as all antenna elements depends on elements next to it. The reason is the series feeding between antennas. Therefore, to reduce the complexities of the monopulse system as the main objectives of the thesis, the series feeding is changed to corporate feeds, also removing differential feeds decreases the no of the ports. The antenna elements now are independent from each other and can be easily matched. The following section shows the new design for the monopulse antenna systems with improved matching and simple design.

3.4 Proposed design

The configuration of the proposed monopulse antenna system is presented in the form of block diagram in Fig. 3-10. The antenna system in this work produces sum and difference radiation patterns in xoz and yoz-planes which is the required information for tracking the target in dual axis. The ratio of difference pattern to sum pattern, (Δ/Σ), in specific axis is known as monopulse function. This information is inserted in equation (iii) to solve for the angle of arrival of the target [10]

For Σ pattern = AoA = $\cos\left[\frac{\beta d}{2}\sin\theta\right]$ (i)

For Δ pattern = AoA = $\sin\left[\frac{\beta d}{2}\sin\theta\right]$ (ii)

$$Monopulse\ function = \frac{\Delta}{\Sigma} = \tan\left[\frac{\beta d}{2}\sin\theta\right], \quad \beta = \frac{2\pi}{\lambda}$$

⇨ AoA = $sin^{-1}\left[\frac{\lambda}{\pi d}\left\{tan^{-1}\left(\frac{\Delta}{\Sigma}\right)\right\}\right]$ (iii)

The circularly polarized antenna is also added to the monopulse system which accepts the incoming wave in both vertical and horizontal polarization thereby minimizing polarization loss of antenna by - 3dB [11]. Polarization loss can be better understood by the PLF (polarization loss factor) which is the ratio of received power in cross polarization to received power in co-polarization as given in equation (iv) [12].

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

According to friss transmission equation lower the PLF greater is the power received by the antenna which is the reason of adding the circularly polarized antenna element to the proposed design.

3.4.1 Radiation Structure

Fig. 3-10 shows the radiation structure along with the comparator network on the same plane as a novelty of the design to reduce complexities. This is the simple geometry which consists of only two couplers for exciting the square patch elements in xoz and yoz-planes using corporate feeding. For the required patterns four inputs are required where each input results in a specific pattern. Port 1 and 3 are the required difference ports which are connected to 50 Ω line by edge mount PCB connectors resulting in difference patterns in $\varphi = 0^o$ (azimuth) and $\varphi = 90^o$ (elevation) planes. For the sum patterns in xoz and yoz-plane, port 2 and 4 is used which is fed from the bottom side of substrate board. The square patch elements are matched to the 50 ohms lines using quarter wave transformer of 0.2 mm width. The reason of the square shape antenna elements is to make the antenna system symmetrical in dual axis. Circularly polarized antenna patch element is added to the upper right corner of the design as shown in Fig 3-10. The purpose of adding this part is to get sum pattern so that to avoid the polarization mismatches for the required patterns for monopulse function. The optimized value of quarter wave transformer is set to 0.5 mm for the circularly polarized antenna.

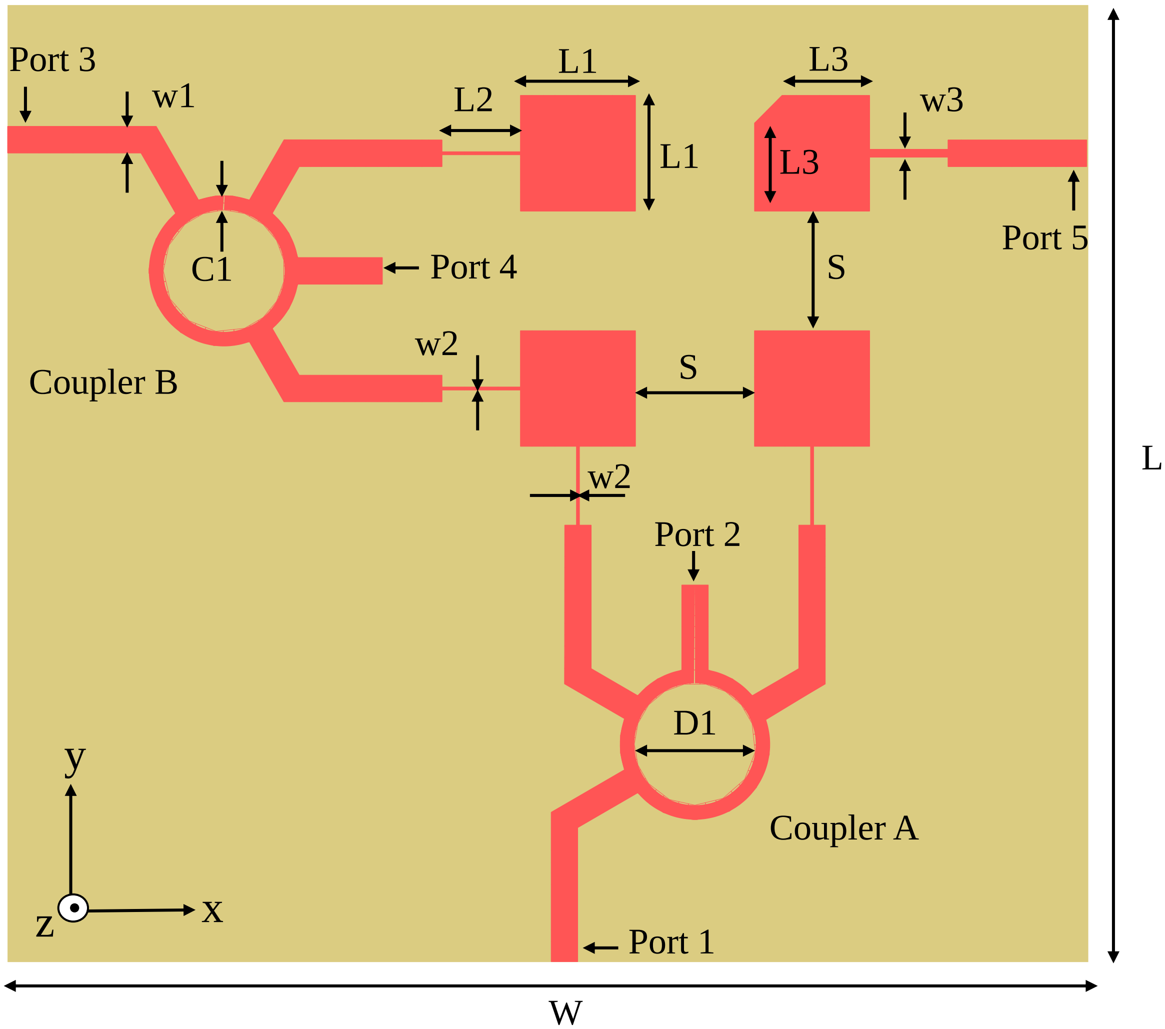


Figure 3-10: Design geometry of the proposed monopulse antenna array

The table 3-2 shows the design parameters for the antenna diagram in Fig 3-10.

Table 3-2: Optimized Design Parameters of The Proposed Monopulse Antenna System (in mm)

w_1	w_2	w_3	l_1	l_2	l_3	c_1	d_1	S	L	W
1.68	0.2	0.5	9.0	4.94	5.54	0.9	7.66	7.5	68.0	

3.4.2 Comparator Feed Network

The comparator part of the proposed antenna system consists of two rat trace couplers placed at right angles to the antenna elements. The couplers are designed for (8 – 12) GHz where -10 dB matching covers the whole band. The output 50 Ω lines of couplers excite the antenna elements out of phase when input is given at port 1 of coupler A and port 3 of coupler B as shown in Fig. 3-10. The same phase excitation is achieved by giving the input to the sum ports 2 & 4 of the couplers. The optimized values of width 1.68 mm are used for the input and output 50 Ω lines of couplers. The phase matched and magnitude balanced microstrip lines have been used to realize the proper radiation patterns.

The S-parameters of the proposed monopulse antenna system which is best matched at 10.13 GHz for the sum and difference ports are shown in Fig. 3-11. Port 2 and 4 have a -10 dB impedance bandwidth of 260 MHz from (10.01 – 10.27) GHz. Likewise, port 1 and port 4 shows -10 dB bandwidth from (10.03 – 10.17) GHz of almost 140 MHz. Port 5 is widely matched from (10.08 – 10.68) GHz with -10 dB bandwidth of 600 MHz. The isolation between ports is an important characteristic in compact antennas. Fig. 3-12 shows the isolation curves between the main ports of antenna which is lower than -20 dB in the whole band of (8 – 12) GHz.

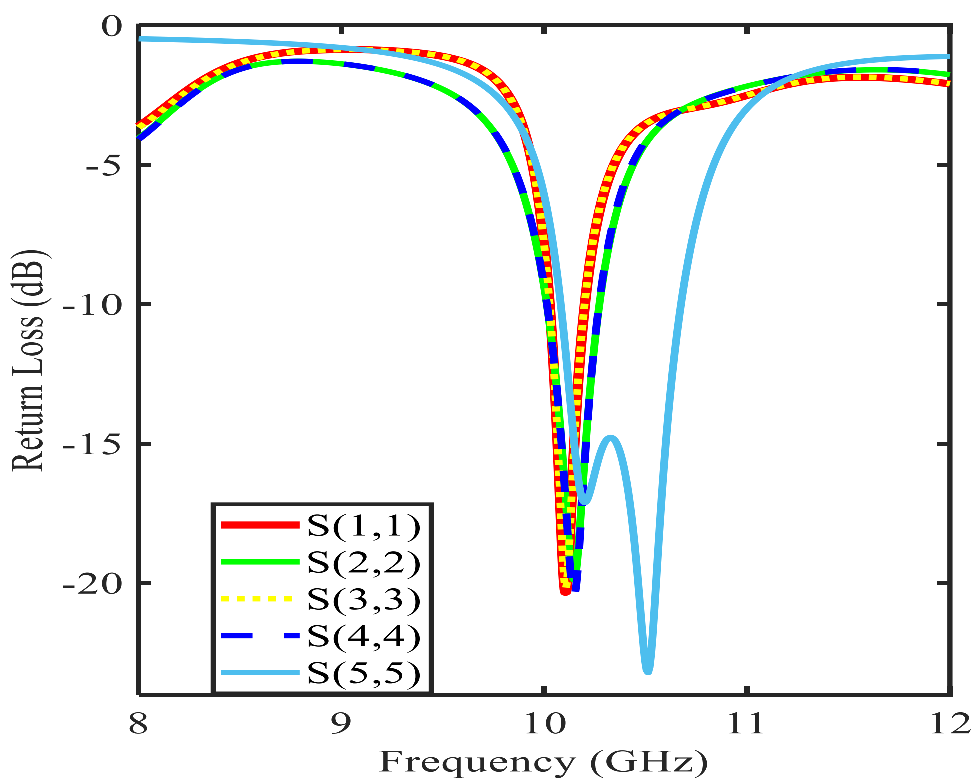


Figure 3-11: S-parameters of five ports of the proposed design

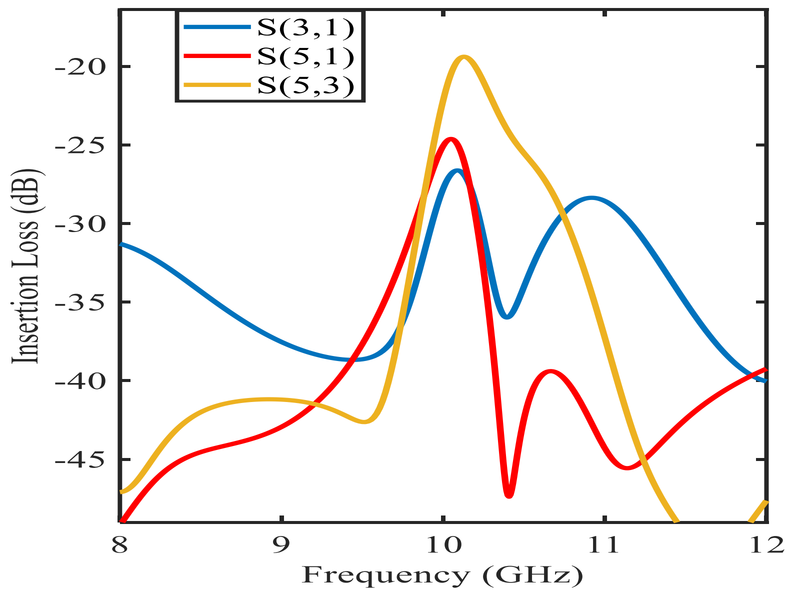


Figure 3-12: Isolation of the port 3 and 5 from port 1

In Fig. 3-13 the sum and difference patterns are shown in xoz and yoz-plane. When a signal is applied to port 1 the difference patterns is obtained in xoz-plane with the null depth of -31.5 dB near -1° at 9.96 GHz. To get the difference pattern in yoz-plane port 3 needs to be excited which gives -31.9 dB null depth around 4° at 9.86 GHz. The signal feeding through Port 2 and 4 results in sum patterns with gain of 9 dBi around 10.35 GHz. The sum pattern with horizontal polarization is achieved using port 2 and with vertical polarization using port 4.

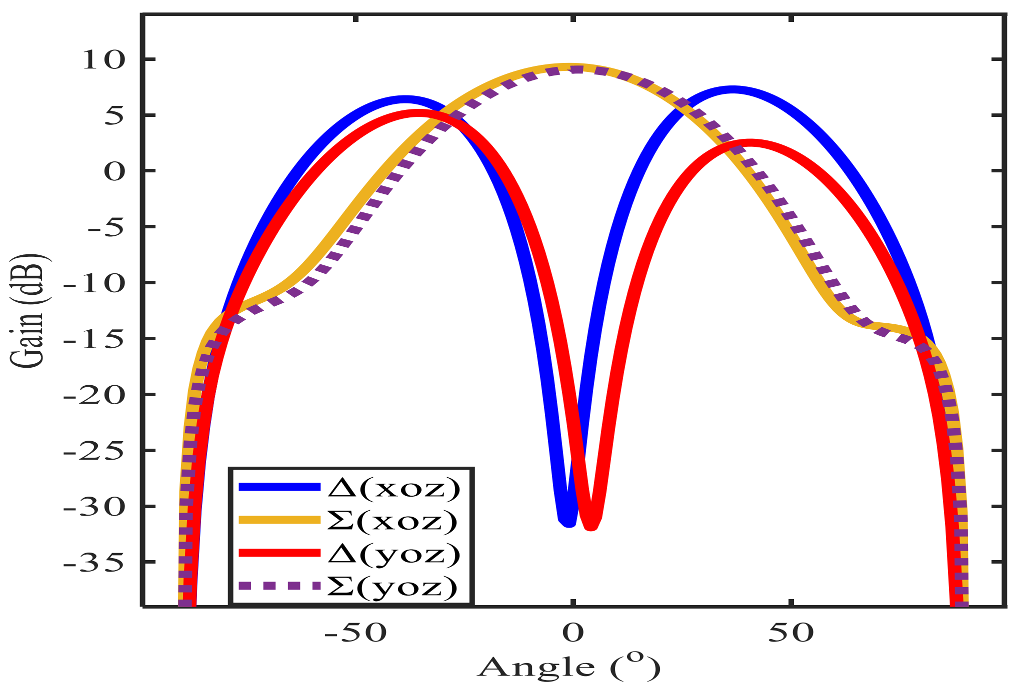


Figure 3-13: Radiation Patterns of sum and difference in two orthogonal palnes.

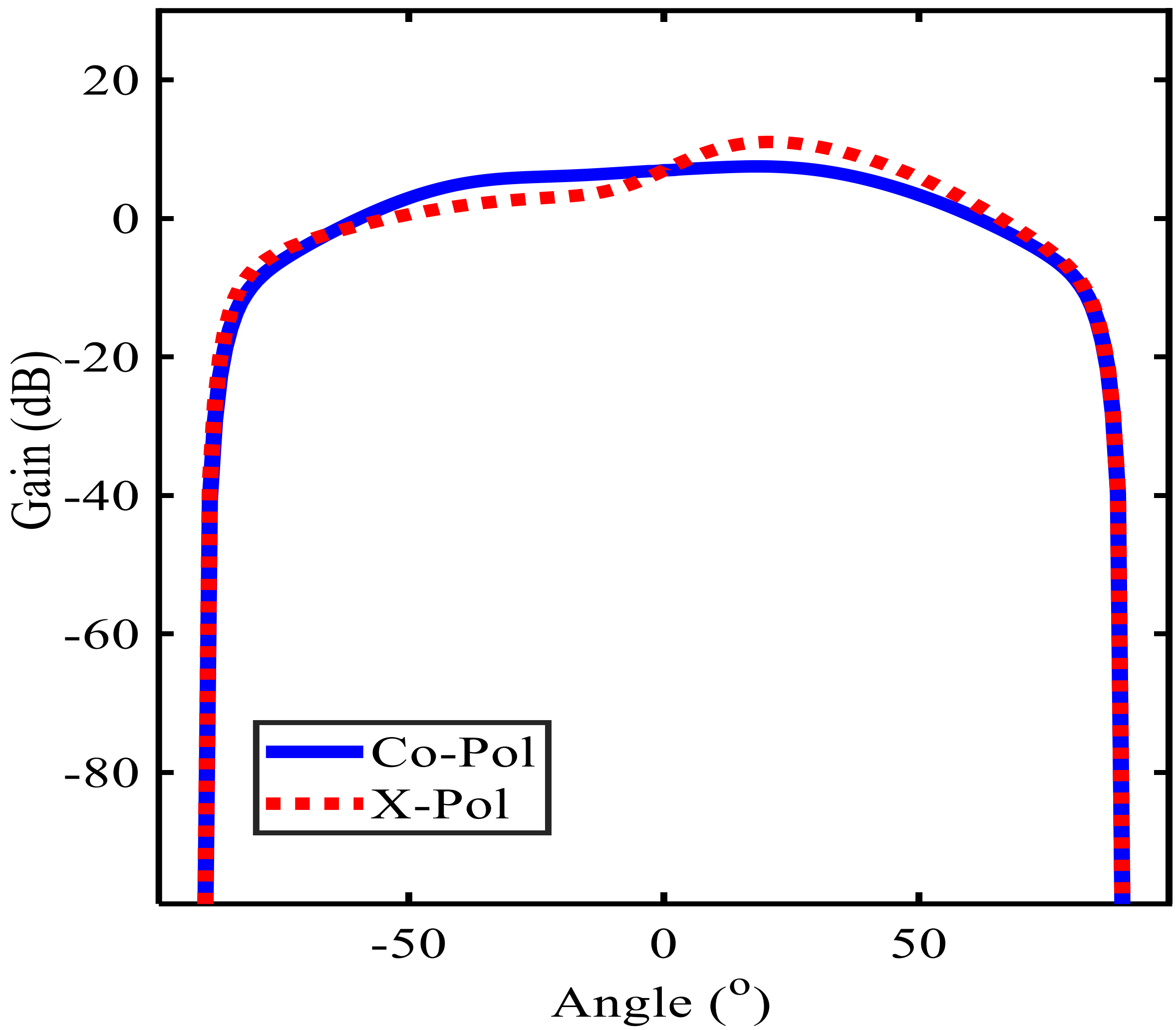


Figure 3-14: Sum pattern of circulary polarized antenna in xoz (x-pol) and yoz (co-pol) planes.

For the dual polarization property signal is given through port 5 which gives 5 dB gain both in vertical and horizontal polarization at 10.1 GHz as shown in Fig. 3-14. This figure also explains the circular polarization due to left upper patch antenna element in the proposed design for monopulse array antenna system.

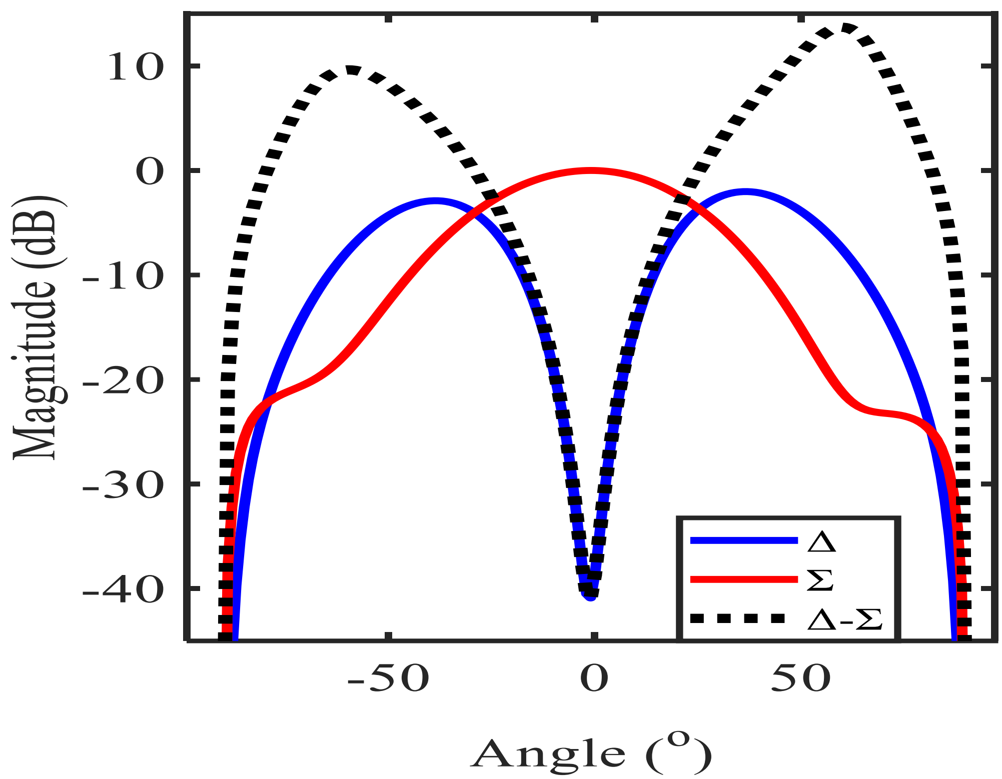


Figure 3-15: Simulated radiation patterns. Δ(xoz), Σ(xoz) and Δ/Σ(xoz) in [φ = 0^o].

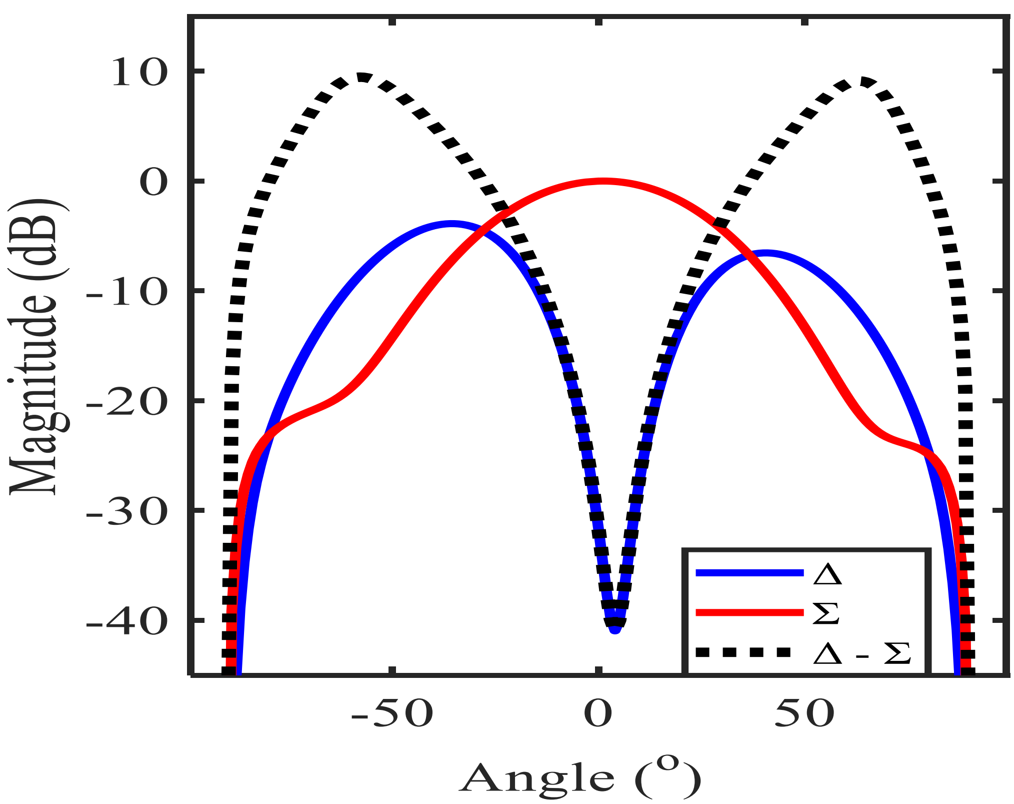


Figure 3-16: Δ(yoz), Σ(yoz) and Δ/Σ(yoz) in [φ = 90^o].

The equation (iii) gives the angle of arrival of the signal when it reflects back from the target. It requires the information of sum and difference of radiation patterns. In Fig. 3-15 the monopulse function is plotted along with the patterns in the monopulse plot in xoz-plane while that in yoz-plane is plotted in the Fig. 3-16. The peaks of the monopulse function are approximately around ± 60° for both orthogonal planes due to symmetry of the design. Fig. 3-17 and 3-18 shows the difference radiation patterns in 3D visualization.

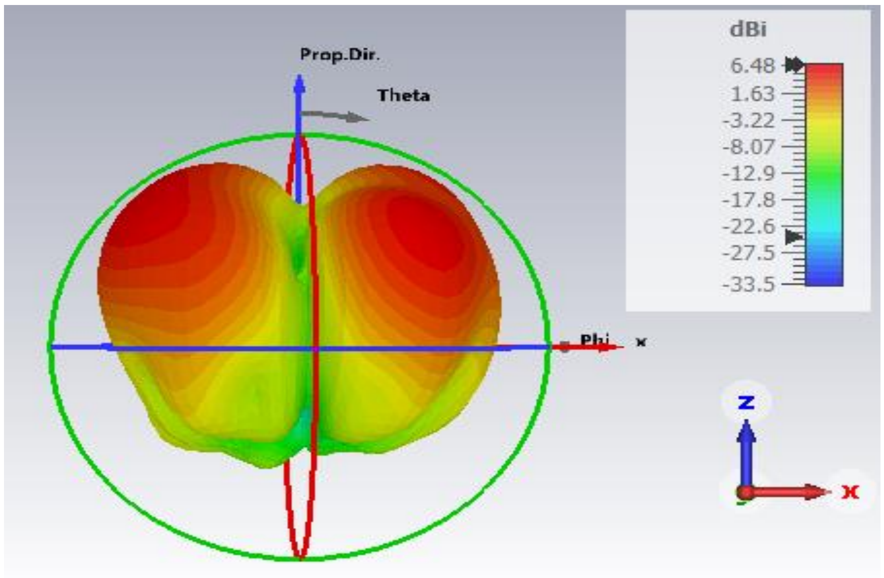


Figure 3-17: Radiation patterns in 3-D. [φ = 0^o] Δ(xoz)

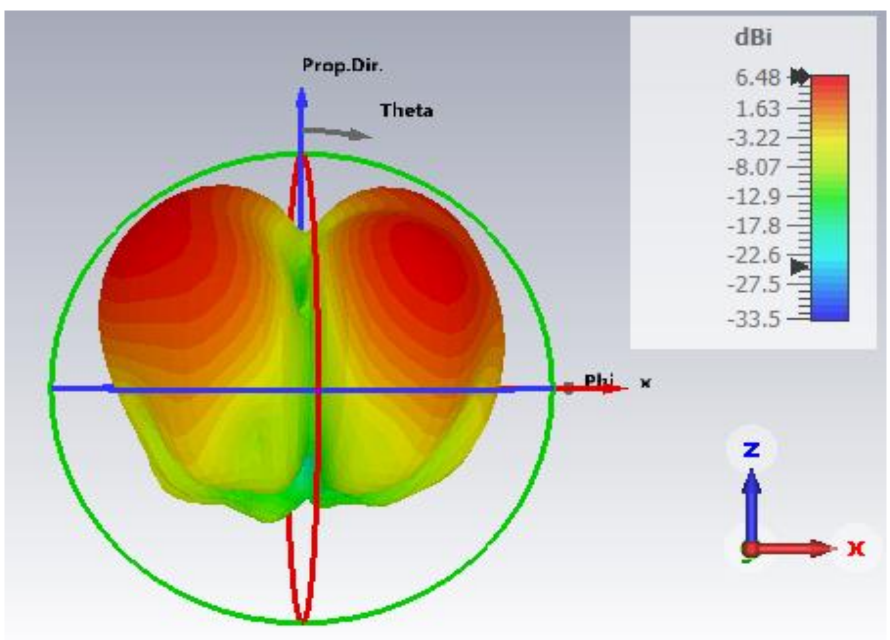


Figure 3-18: Radiation patterns in 3-D. [φ = 90^o] Δ (yoz)

3.5 180^0 Hybrid Coupler

Hybrid coupler uses four ports for its operation. It can work as divider or combiner. Also known as rat-race coupler, it has 2 input ports, sum port and difference port. As a combiner, when inputs are given at port 2 and 3, it gives the sum and difference at port 1 and port 4. As divider, when signal is given at port 1 which is the sum port, then port 2 and port 3 gives output signals with same phase. When signal is given at port 4, which is difference port, the coupler gives output at port 2 and 3 with 3 dB loss in magnitude and with phase variation of 180 degrees. As it can also be seen in the figure 3-10, that from port 2 and 3, the electrical distance is same to port 1 while it is different for port 4, due to which the sum and difference patterns are achieved.

The length and width of the circle part is determined by EM calculator. The width is according to 70.7 ohms while the length is based on electrical length of overall 540 degrees, which is circumference of circle. The radius of the circle of the rat-race coupler is determined by the following simple formula:

$$C = 2\pi r$$

$$r = \frac{C}{2\pi}$$

The rat-race coupler is made at the same design frequency and substrate as for the 2x2 patch array monopulse antenna system as shown in Fig. 3-19. This coupler has been integrated with the array and work as comparator to provide the sum and difference patterns required for the monopulse function to find the detect the exact angle from which it will receive the signal. The advantage is that it can find this angle both in elevation as well as azimuth plane due to the geometry of the proposed monopulse antenna system.

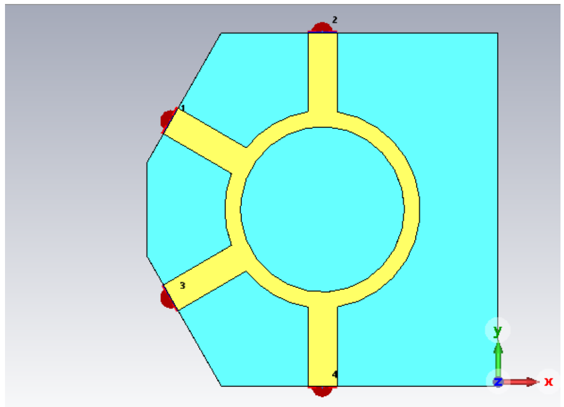


Figure 3-19: Design of rat-race coupler

3.5.1 S-Parameters of the Rat-Race Coupler

After simulations of the rat-race coupler the following results of the S-parameters are obtained shown in Fig. 3-20. As expected, these are wideband couplers, as can be seen from the following results. S11 and s33 shows the same response with the -10 dB bandwidth almost covering most of the range of the X-band. S22 and s44 are full matched for the entire range of frequencies as its obvious from the following figure.

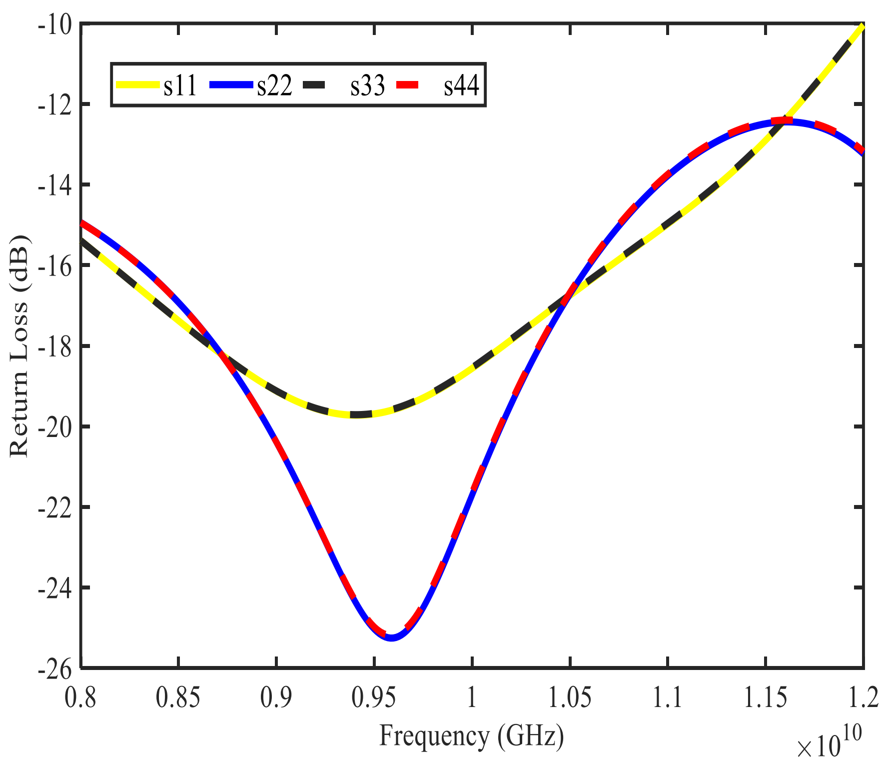


Figure 3-20: S-parameters of the rat-race coupler

3.5.2 Insertion Loss of the Rat-Race Coupler

Couplers in general are designed to have loss of 3 dB when a signal propagates from one port to another. So, it is necessary to check not only for the matching of all ports, but also if the insertion loss is around 3dB, as much losses will have effect on the overall performance of coupler. The Fig. 3-21 shows the insertion loss of the designed coupler, which is very near to the required value of 3 dB at the designed frequency. This means that it can be used to work as comparator for the monopulse antenna system.

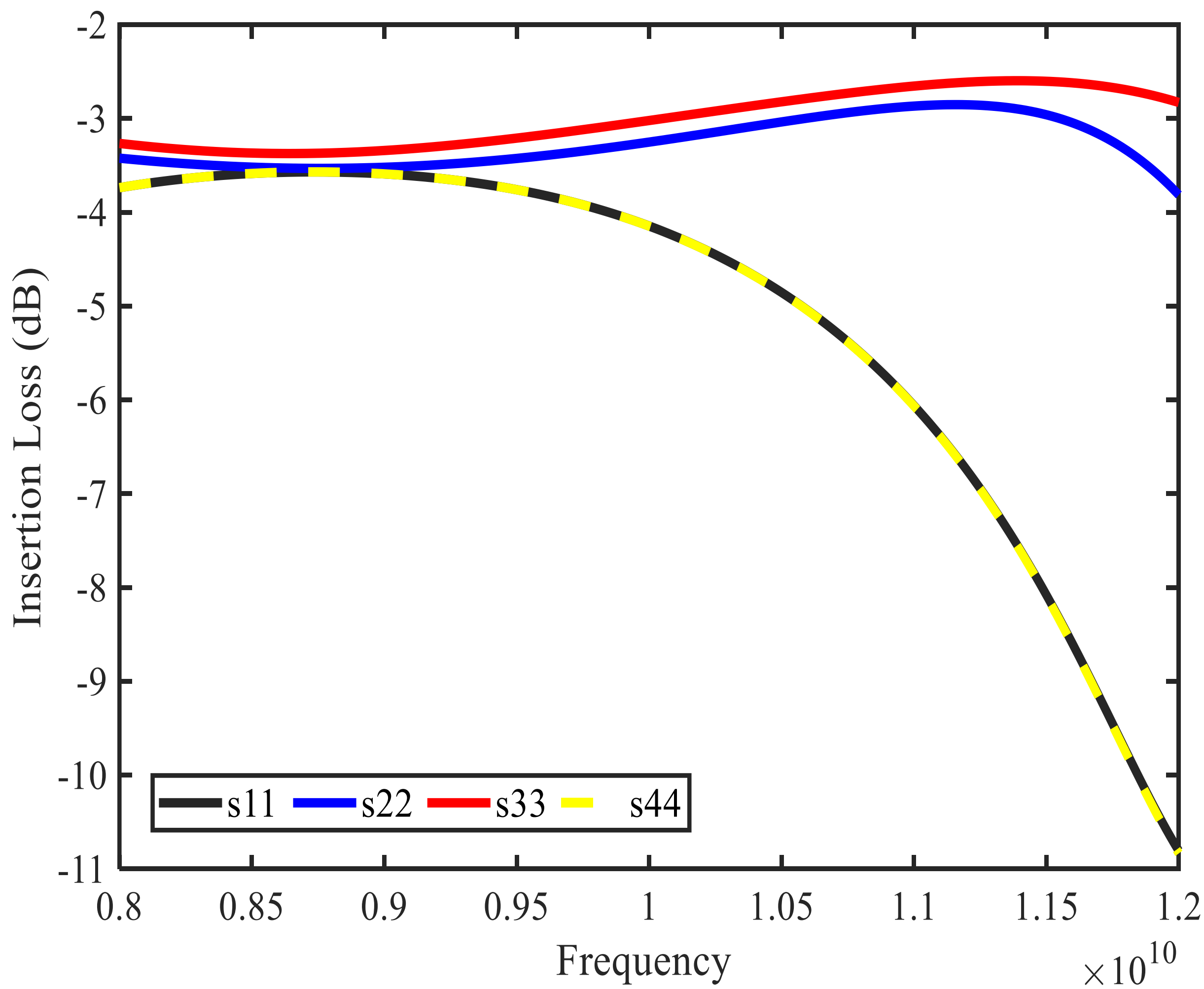


Figure 3-21: Insertion loss of the rat-race coupler

3.5.3 Sum Port of the Rat-Race Coupler

This section describes the behavior of the sum port. As required from the sum port of a rat-race coupler it should completely sum up the incoming signals, as the distance from the input ports to sum ports is same. this can be verified by checking the phase difference of the signals coming from port 2 and port 3 to the sum port which is port 1. As can be seen in the Fig. 3-22, the phase difference is almost zero degrees between the two input signals at the sum port, which means these signals will constructively add up here.

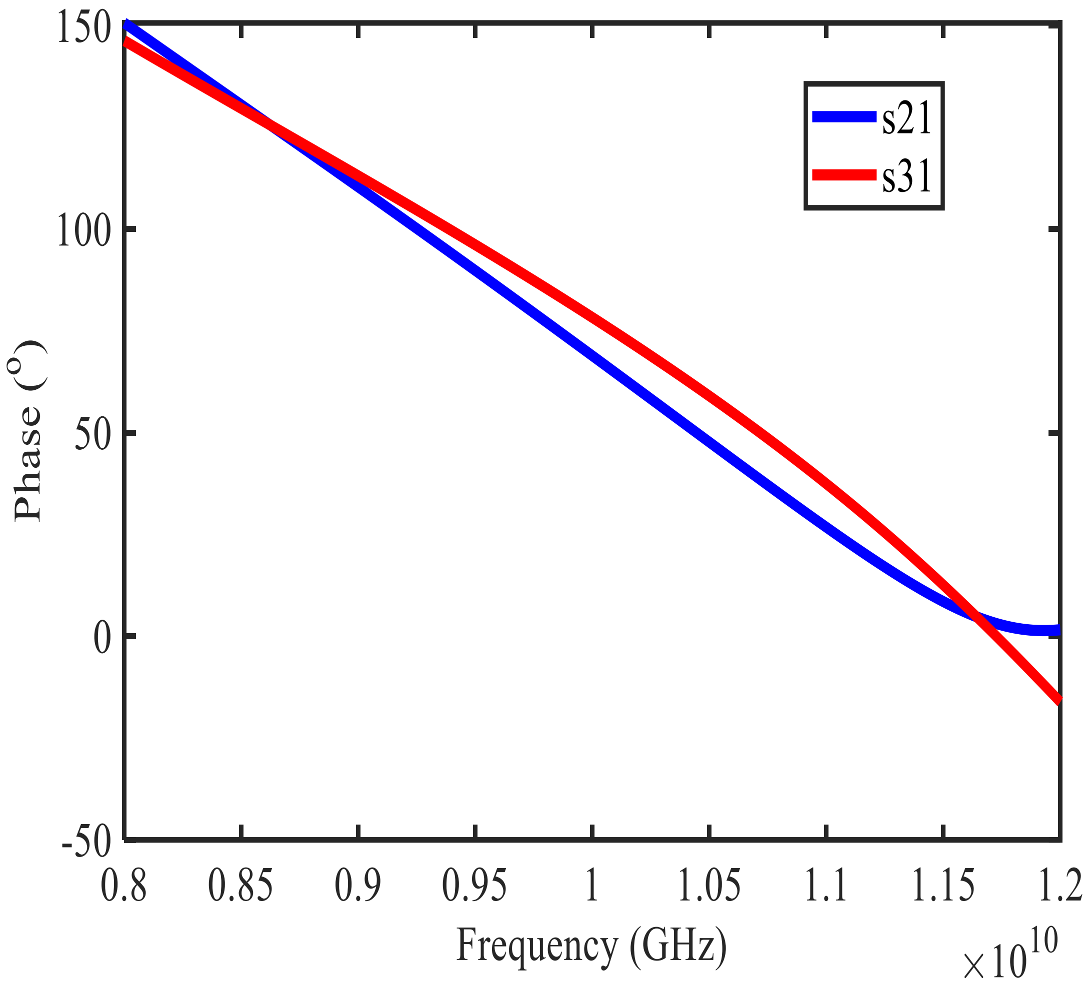


Figure 3-22: Phase response of Sum Port

3.5.4 Difference Port of the Rat-Race Coupler

The phase of the difference port of the rat-race coupler is required to be 180 degrees, so that to cancel out the incoming signals. As for monopulse function along with the sum pattern, there is also required difference pattern, so the difference port of this coupler is best option is used. The following figure shows the phase response of the difference port of the designed coupler. From the results in Fig 3-23, it is verified that the incoming signals can be exactly added with 180 degrees phase difference, at the difference port of this coupler.

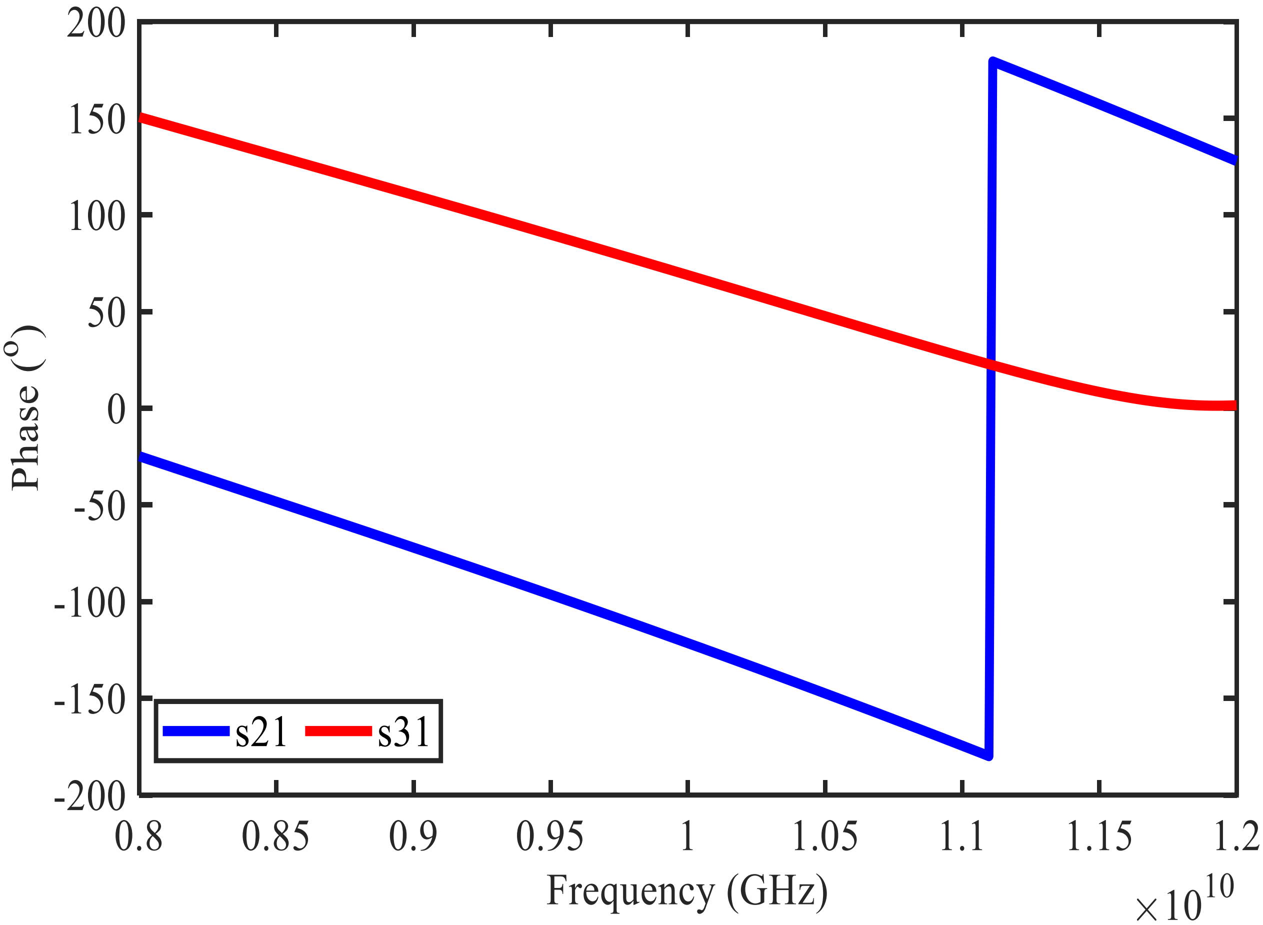


Figure 3-23: Phase response of difference Port

3.6 Summary

In this chapter the design process of monopulse antenna system is explained in details with very good results compare to the literature. The 2x2 antenna array is made with combination of only two rat-race couplers in such a way to work as monopulse comparator on a single layer. The radiation patterns are shown which shows acceptable null depths for the difference patterns. Overall, the whole antenna is very compact as compare to the literature. The rat-race couplers are made at x-band and after verification of the results, they are integrated with the antenna array.

Chapter 4. FABRICATION RESULTS AND DISCUSSIONS

This chapter presents the simulated and experimental results of the proposed monopulse antenna system. The sum and difference patterns in elevation and azimuth are also discussed in details which shows that the antenna system can be used in tracking radars systems.

4.1 Fabrication details

For the verification of proposed design of the monopulse antenna system the 2×2 array in combination with the two rat-race couplers are fabricated on the Rogers 4350b substrate with basic characteristics (permittivity, ε_r= 3.66, Dielectric constant, tanδ = 0.004 and thickness, h = 0.762 mm). Two 90^{o} sma connectors are connected to both difference ports so that the cable can be connected at the back of radiation part to minimize the ripples in these sensitive difference patterns. The sma connectors for the sum ports are soldered at the back side of antenna. The photograph of the fabricated antenna with front and backside is shown in Fig. 4-2 and Fig. 4-3 respectively.

4.2 Anechoic Chamber Setup for Testing

To characterize the 2-D radiation pattern in an anechoic chamber, a standard horn antenna used as a transmitting antenna which is kept at 3.40 m from the antenna under test. The power is received by the antenna under test with scanning rate of 4.4 deg/sec. The radiation pattern of the presented array antenna has been tested in the 360^{o} span in theta = 180 degrees to – 180 degrees for phi = 0 degree and 90 degrees as shown in Fig 4-1.

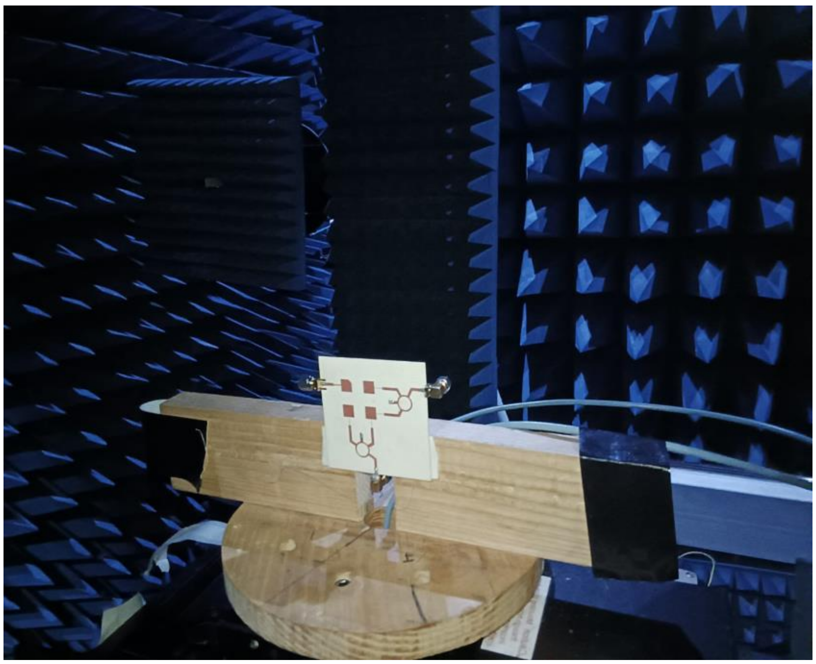


Figure 4-1: Photograph of the proposed antenna in anechoic chamber

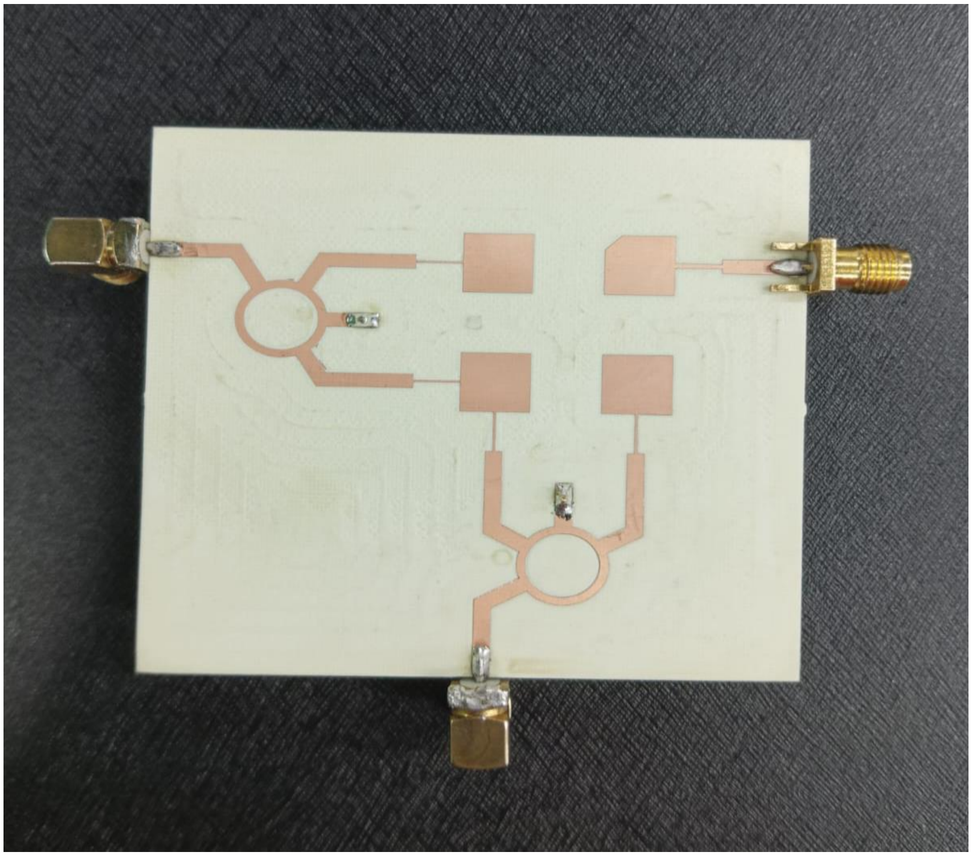


Figure 4-2: Front Side: Photograph of proposed monopulse antenna system

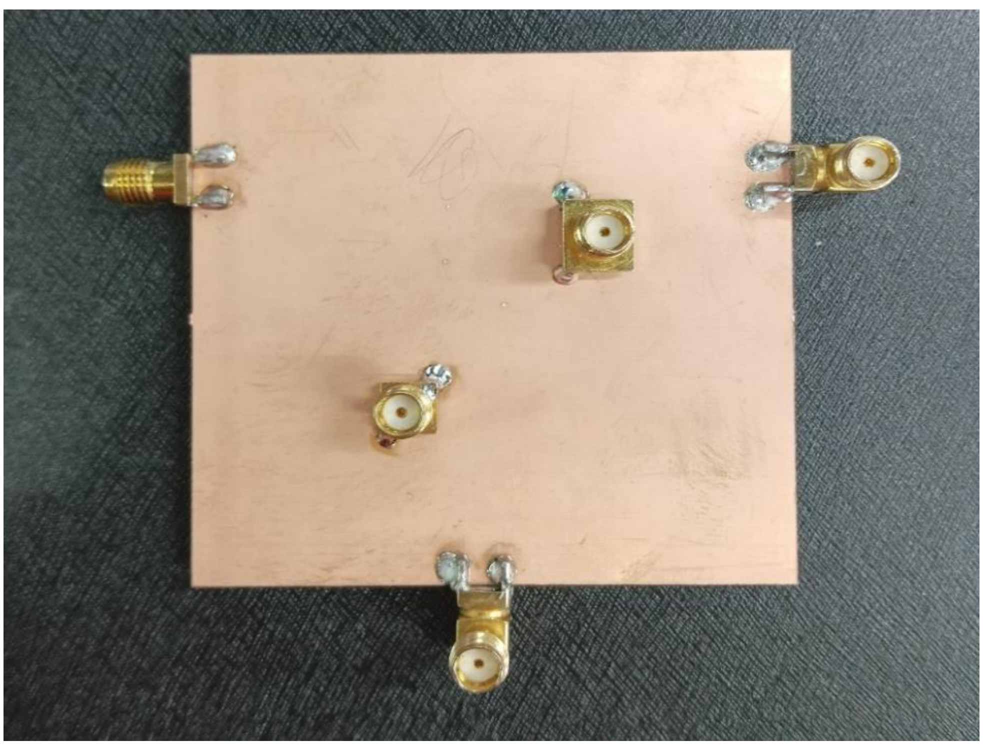


Figure 4-3: Back Side: Photograph of proposed monopulse antenna system

4.3 Measured S-parameters

Fig. 4-4, shows the measurement results for the proposed antenna. The port 1 of coupler A resonates at 9.94 GHz with -27.89 dB return loss and -10 dB bandwidth from (9.85 – 10.04) GHz. The sum port, port 2, of coupler A is less matched according to measured values compared to other ports with return loss of -9.5 dB at 10 GHz due to port connectivity issues from the bottom of substrate. Port 3 of coupler B is matched from (9.91 – 10.09) GHz with return loss of -29 dB at 10 GHz. Port 4 shows wideband of -10 dB from (9.04 – 10.3) GHz with return loss of -27 dB at the resonant frequency 9.97 GHz. The circularly polarized patch resonates at 10.6 GHz with -15 dB return loss. The patch element has sum patterns in xoz and yoz-plane which resembles more at 10.1 GHz showing the antenna is circularly polarized at this frequency.

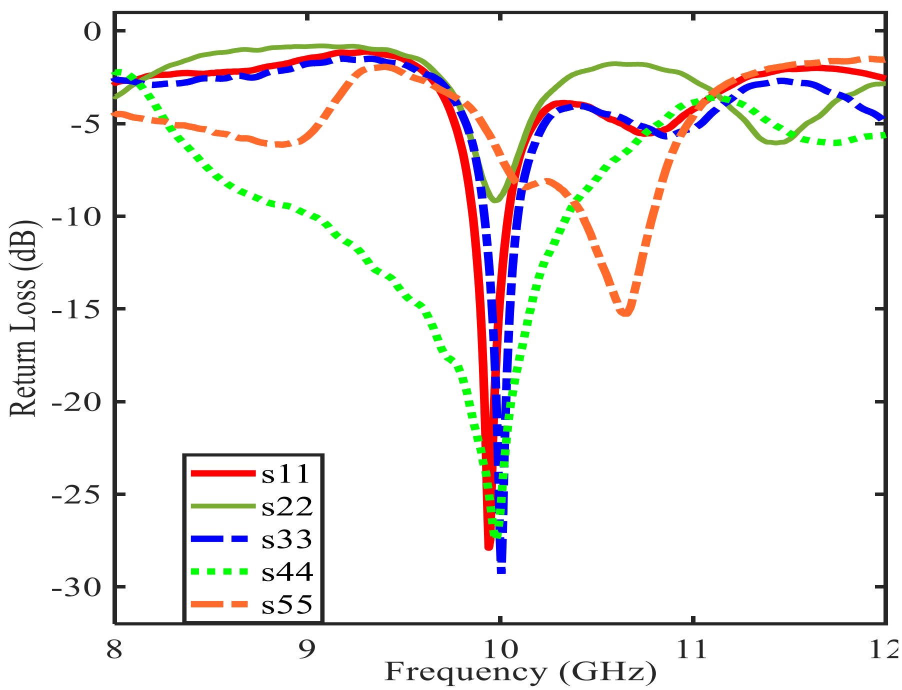


Figure 4-4: Measured S-parameters.

4.4 Measured Radiation Patterns

The circularly polarized patch resonates at 10.6 GHz with -15 dB return loss. The patch element has sum patterns in xoz and yoz-plane which resembles more at 10.1 GHz showing the antenna is circularly polarized at this frequency. Applying signal on port 5 for the circular polarization feature of antenna system gives the sum patterns which are measured in xoz and yoz-plane to check the resemblance between the patterns. The measured results shows that these patterns are similar from (-40^{o} – 40^{o}) validating the circular polarization around 10.1 GHz as shown in Fig. 4-5.

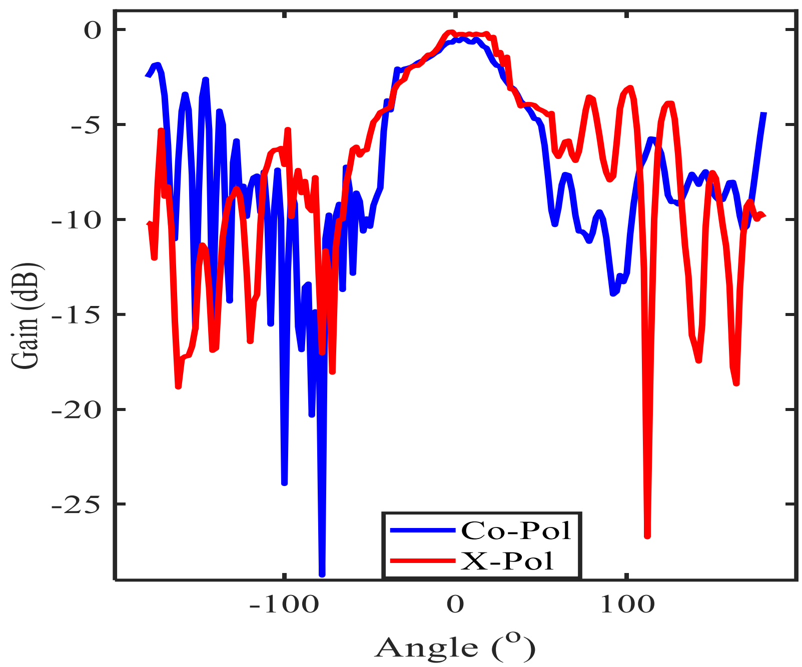


Figure 4-5: Measured Sum pattern of circulary polarized antenna in xoz (x-pol) and yoz (co-pol) planes.

The measured radiation patterns of the proposed antenna are mentioned in figure 4-6. The difference and sum patterns in xoz-plane results from the excitation of port 2 and port 1 of the coupler A respectively. The measured difference pattern due to port 1 has -13.5 dB null depth at 4°. The sum pattern in xoz-plane is obtained from port 2 with side lobes lower than -20 dB.

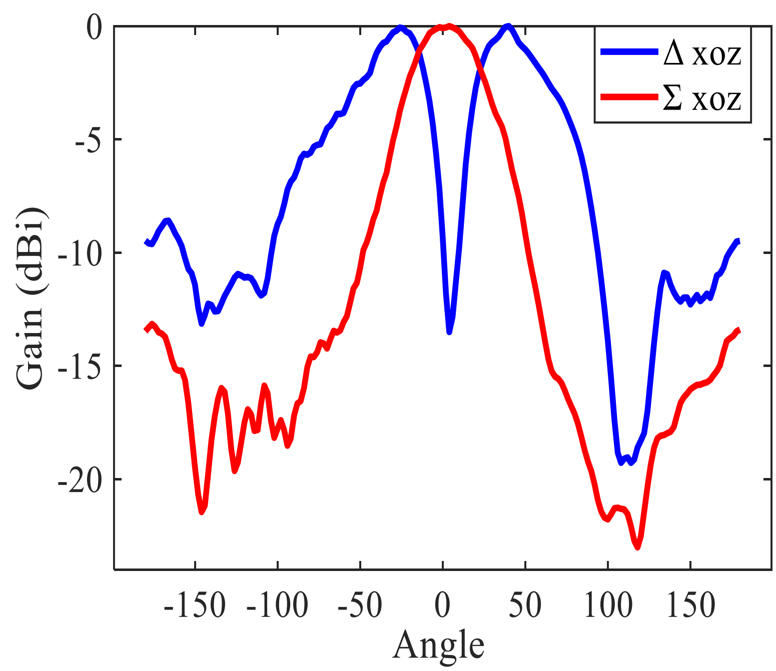


Figure 4-6: Measured patterns: Radiation Patterns of sum and difference in xoz palne.

The antenna patterns are also measured in yoz-plane as shown in Fig. 4-7, when signal was given through coupler B. Port 3 of this coupler give a difference pattern which has null depth of -18.65 dB exactly at 0^o. The ripples in these patterns are due to port 1, 3 and 5 as these are connected at the edges of substrate board.

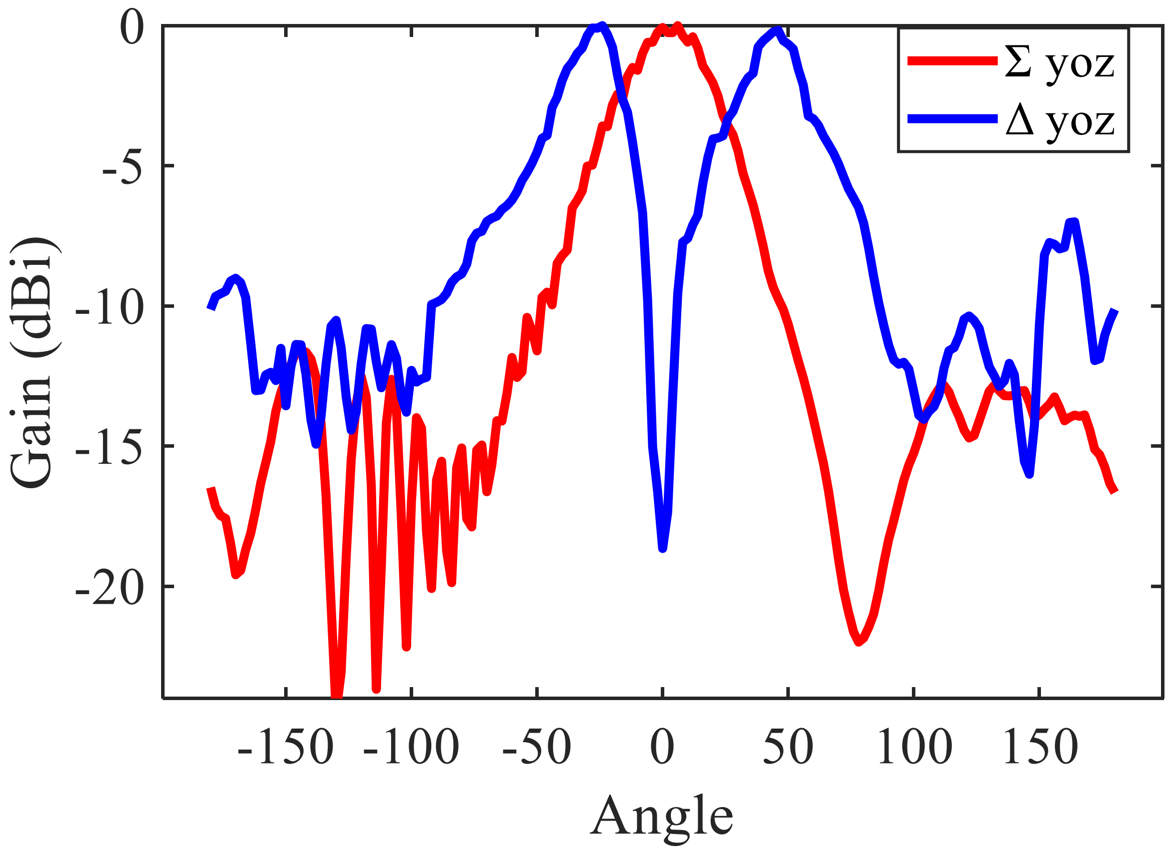


Figure 4-7: Radiation Patterns of sum and difference in yoz-plane.

Fig. 4-8 shows the measured patterns of sum and difference patterns in xoz and yoz-planes. The antenna is rotated in chamber from $\theta = -180^o$ to $\theta = +180^o$ for $\varphi = 0^o$ (azimuth) to get pattern in xoz-plane and $\varphi = 90^o$ (elevation) for patterns in yoz-plane as shown in Fig. 4-9. The required monopulse function is calculated from the measured patterns in both planes. The ripples in plot of monopulse function is the result of ripples in sum and difference patterns mainly due to the connectors at the edges of the substrate board and also different limitations in fabrication.

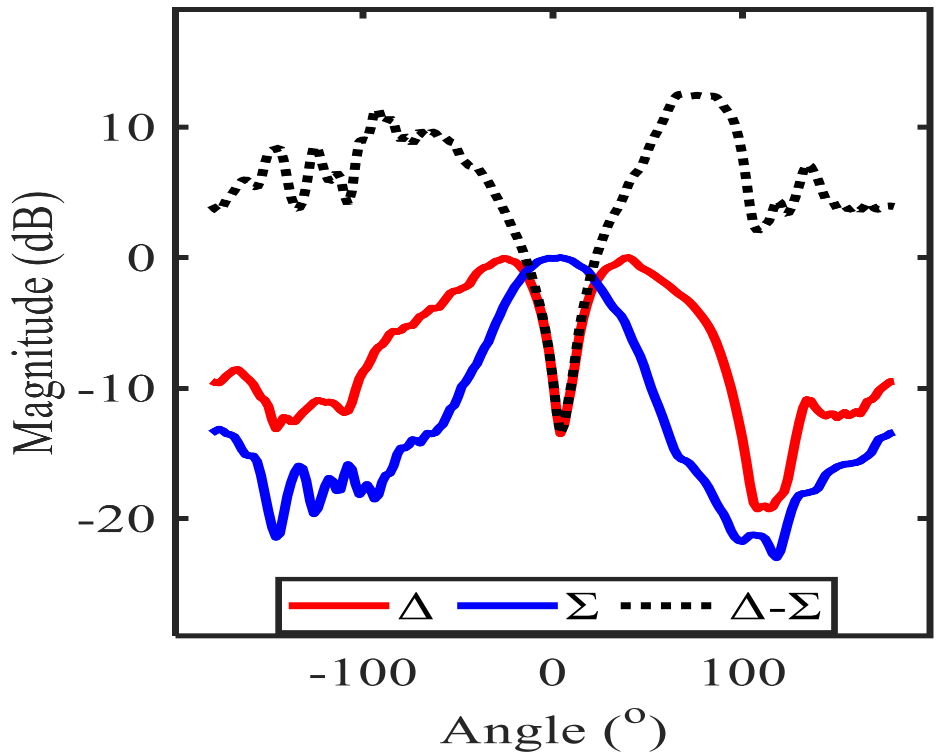


Figure 4-8: Measured radiation patterns. Δ(xoz), Σ(xoz) and Δ/Σ(xoz) in [φ = 0^o].

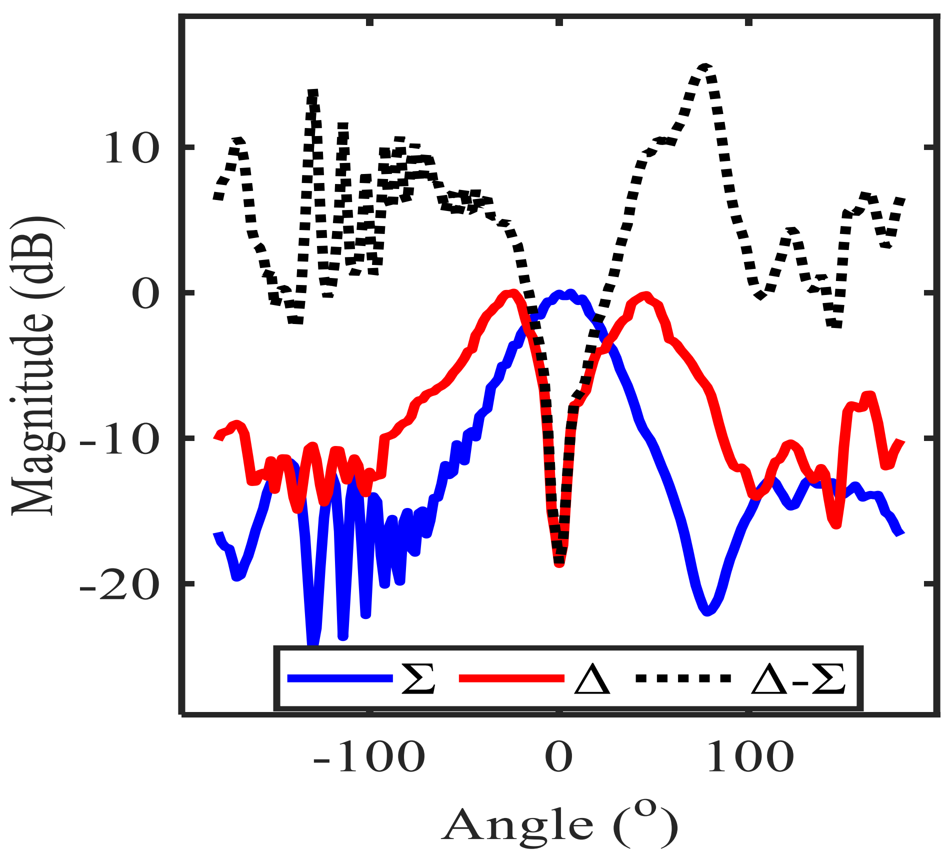


Figure 4-9: Δ(yoz), Σ(yoz) and Δ/Σ(yoz) in [φ = 90^o].

Table 4-1: Comparison of this work with state-of-the-art monopulse antenna systems

Ref.	Paper (year)	Frequency	No of layers	No of Couplers	Angle of Arrival Direction	Null depths
[4]	IEEE AWPL (2019)	9 – 11 GHz	2 (Complex geometry)	4	Dual- axis	Azimuth = -20 dB & Elevation = -24 dB
[5]	AP-S 2016	BW of 13.9 % around 9 GHz	2 (Complex geometry)	4	Dual-axis	Better than -30 dB
[6]	IEEE Transactions (2006)	13.85 – 15.1 GHz, BW = 5.6 %	2 (Complex geometry)	4	Dual axis	Less than -30 dB
[7]	Electronics Letter (2003)	Ka- Band	1 (simple)	1	Single axis	-30 dB
[8]	IEEE MWCL (2016)	2.11 – 2.45 GHz	1 (simple)	1	Single axis	-32.7 dBi
[9]	IEEE AWPL (2009)	5.05 – 6.67 GHz	2 (Complex)	4	Dual axis	-28 dB
This Work	N/A	X-Band (10 GHz)	1 (simple)	2	Dual axis	-32 dB

The above table shows that most of the monopulse antennas in the literature are multilayer and consist of complex comparators. The multilayer configurations can obtain the AoA information in azimuth and elevation. Some of the paper also shows single layer design but the drawback is that it can only measure the AoA in single axis. In this work both the advantages are combined in a single design. The proposed design is very simple and single layer. There are only two rat-race couplers used. Still, it can measure the AoA in dual axis.

Chapter 5. CONCLUSION & FUTURE RECOMMENDATIONS

5.1 Conclusion

In this work, a monopulse antenna system is designed, for the radar applications to accurately detect the angle of the incoming signals from the target. This thesis proposes new idea for the monopulse antenna system based on a single layer planner antenna array. Along with antennas, the 180 degrees ring hybrid coupler is designed to provide the sum and difference patterns for the monopulse function which is the ratio of difference and sum pattern. A single layer monopulse antenna system is presented for finding the angle of arrival in tracking radars. The antenna system is designed for X-band which works best at 10 GHz. The same concept can be employed for lower or upper frequency bands depending on the applications. The whole design is only 68×68 mm which is suitable for compact and low-profile systems. The comparator part consists of only two 180^{o} hybrid couplers with 2×2 antenna array as radiation part. The antenna system can be excited with four horizontal ports for sum and difference patterns in azimuth plane. For the elevation plane, the two ports connected in vertical axis can be excited for these patterns. Overall, the antenna efficiency is more than 70 %. The gain of the array reaches more than10 dBi. Polarizations are achieved in dual axis by changing the excitation of ports. The patterns achieved from simulations and measurements are in acceptable range, which can be used in the formula of monopulse function to precisely find the angle of the signals coming from the targets.

5.2 Future Recommendations

This works presents the simplest topology of the monopulse antenna system in terms of the monopulse comparator part of the antenna system. In future this design can be improved by using the differential fed antennas as radiator part of monopulse antenna systems to reduce the spurious radiations of the feeds. This will improve the radiation patterns even more as radiation characteristics are the critical point of considerations in monopulse antenna system for the detection of the angle of arrival of targets in tracking radars applications.

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