Reflectarray Antenna for Beam Steering Application

M. Tech. Thesis

By

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DEPARTMENT OF ELECTRICAL ENGINEERING

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A THESIS

Submitted in partial fulfillment of the
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Sushovan Chowdhury

DEPARTMENT OF ELECTRICAL ENGINEERING
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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **REFLECTARRAY ANTENNA FOR BEAM STEERING APPLICATION** in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** and submitted in the **DEPARTMENT OF ELECTRICAL ENGINEERING, Indian Institute of Technology Indore**, is an authentic record of my own work carried out during the time period from July 2024 to May 2025 under the supervision of Dr. Saptarshi Ghosh, Assistant Professor, IIT Indore.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institute.

Sushovan Chowdhury

Signature of the student with date
Sushovan Chowdhury

This is to certify that the above statement made by the candidate is correct to the best of my/our knowledge.

Saptarshi Ghosh

28-06-2025
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Mr. Sushovan Chowdhury has successfully given his M. Tech. Oral Examination held on **07/05/2025**

Saptarshi Ghosh
Signature of Supervisor
Date: 28-06-2025

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Signature of Convener, DPGC-EE
Date: 28-06-2025

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Sushovan Chowdhury

ACRONYMS

ABS – Acrylonitrile Butadiene Styrene

BW - Bandwidth

CP – Circular Polarization

DRA - Dielectric Resonator Antenna

EM – Electromagnetic

EP – Elliptical Polarization

HFSS – High Frequency Structure Simulator

ISARA – Integrated Solar Array and Reflectarray

LHCP - Left Hand Circular Polarization

LP – Linear Polarization

PA – Phased array

PLA – Polylactic Acid

RA - Reflectarray

RHCP – Right Hand Circular Polarization

RF – Radio Frequency

TA - Transmitarray

UHF – Ultra High Frequency

VHF – Very High Frequency

VNA – Vector Network Analyzer

Abstract

This thesis presents a new reflectarray (RA) antenna design specifically developed for the X-band frequency range (8–12 GHz), utilizing advanced three-dimensional (3D) printing methods. The proposed RA demonstrates outstanding performance, achieving a minimal reflection loss of just 0.01 dB and offering a comprehensive phase adjustment capability of 360° (spanning from -180° to +180°), which is crucial for supporting wideband applications in modern communication systems. The design also delivers a significant gain improvement, surpassing 19.50 dB at a beam-steering angle of 55 degrees, illustrating its effective beam steering functionality.

Employing 3D printing technology exclusively for fabrication not only lowers production cost and reduces the overall weight, but also increases the design flexibility. The RA is constructed with an ABS substrate (bottom layer) that is 1.6 mm thick and features a periodicity of 8.5 mm, resulting in a lightweight and versatile structure suitable for practical use. This research makes a meaningful contribution to the field of reflectarray antennas.

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Chapter 1

Introduction

1.1 X-Band Communication:

X-band communication utilizes electromagnetic (EM) waves in the range of 8 GHz to 12 GHz, which falls within the Super High Frequency (SHF) segment of the EM spectrum. This frequency band is particularly valued in communication and radar systems due to its unique combination of technical and operational advantages. The details about the frequency bands are illustrated in Figure 1.1.

1.1.1 Characteristics of X-Band

- **Frequency Range and Position:**
- ❖ The X-band occupies the 8–12 GHz range, with wavelengths between 2.5 and 3.8 centimeters.
- ❖ In the frequency spectrum, it is between the C band (4-8 GHz) and Ku band (12-18 GHz) and provides a balance of characteristics from both lower and higher frequency bands.

- **Operational Benefits:**
- ❖ **Versatility in Applications:**

  X-band is widely used for satellite communications (both fixed and mobile), Earth observation, weather monitoring, air traffic control, maritime navigation, and defense tracking.

❖ **Global and Remote Coverage:**

X-band satellites can provide broad coverage, including remote and maritime regions, thanks to their large spot beams and global beam capabilities

- **High Link Availability**

Due to its resilience to atmospheric conditions, X-band links can achieve availability rates exceeding 99.9%, which is critical for mission-essential communications

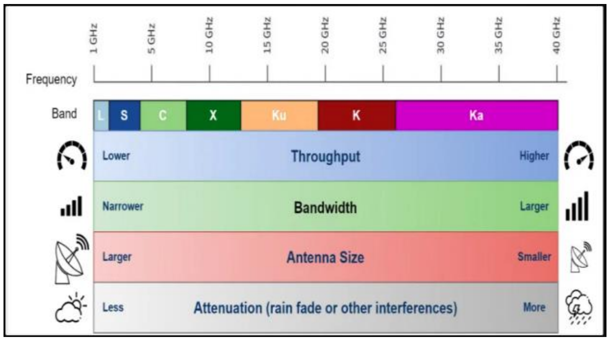


Figure 1.1: Frequency bands for satellite communication(image credit: DOLPH MICROWAVE)

- **Propagation:**

X-band signals are known for their ability to travel long distances and maintain strong performance in communication and radar systems. They are less affected by atmospheric factors like clouds and precipitation when compared to higher frequency bands, allowing them to deliver consistent results in a variety of weather conditions. This makes X-band technology especially reliable for applications that require dependable operation regardless of the environment.

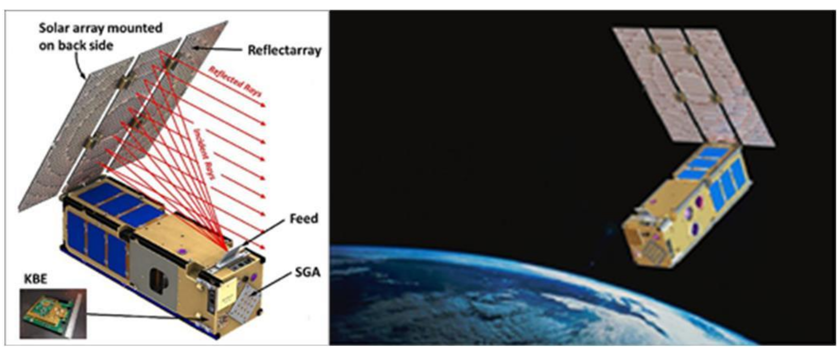
- **Key Applications**
- **Radar Systems:**

  X-band radar systems are widely used for weather monitoring, air traffic control, maritime surveillance, and military applications. The shorter wavelengths of X-band radar enable high-resolution imaging and accurate target detection.

- **Point-to-Point Links:**

  X-band frequencies are frequently chosen for terrestrial microwave communication systems that connect fixed sites, such as network centers, data facilities, and distant locations. These links can support large volumes of data transfer, making them ideal for high-speed communication needs between stationary points.

1.1.2 Satellite Communications:



(a) (b)

Figure 1.2: (a) Reflectarray operational principle, (b) configuration of the ISARA spacecraft with Reflectarray Antenna (image credit: NASA/JPL).

A significant number of communication satellites make use of the X-band because it supports fast data transfer and maintains stable connections, which are essential for services like TV broadcasting, high-speed internet, and secure communications for defense purposes. The ISARA spacecraft features innovative reflectarray antenna (RA) technology, which optimizes how signals are transmitted and received in orbit. As depicted in Figure 1.2, this advanced setup demonstrates improved communication performance. ISARA serves as an important platform for testing and advancing space-based communication technologies.

1.1.3 Antenna Requirements

- **Antenna Size:**

  Because X-band operates at higher frequencies, the antennas required for these signals can be made more compact than those used for lower frequency bands. This reduced size allows them to be easily integrated into portable devices and systems where space is limited.

- **High Gain:**

  X-band antennas used for radar and remote communications generally require high gain. Array and parabolic dish antennas are frequently used to gain direction.

1.1.4 Advantages of X-Band

- **High Data Rates:**

  X-band is particularly advantageous for scenarios where rapid data exchange and minimal delay are essential. Because this frequency range can handle substantial amounts of information at high speeds, it is ideal for various cases, such as scientific data collection, military operations, and Earth observation, where quick and reliable transfer of large datasets is required.

- **Reliable Performance:**

  X-band is recognized for its dependable performance in situations where communication cannot be compromised. One of its key strengths is its ability to maintain strong signal quality even when faced with adverse weather, such as rain or heavy clouds-a challenge that often disrupts higher frequency bands like Ku and Ka. This weather resilience ensures that X-band links remain stable and trustworthy, which is especially important for tasks like military operations, emergency response, and environmental monitoring.

1.2 Antenna Fundamentals:

- ❖ Antennas play a vital role in communication systems by enabling the transmission and reception of electromagnetic signals. Having a solid grasp of how antennas work and the principle behind their operation is essential for designing communication networks that are both reliable and efficient.
- ❖ At their core, antennas act as a bridge between electrical circuits and the open air, converting electrical signals into electromagnetic waves for broadcasting, and vice versa for reception. Their effectiveness depends on several factors, including their shape, size, orientation, and how well they are matched to the system's frequency. The way an antenna directs its energy whether in all directions or focused on a specific path can significantly impact the coverage and strength of a communication link.
- ❖ Other important considerations include the polarization of the signal, which should match between transmitting and receiving

antennas for optimal performance, and the antenna's gain, which determines how efficiently it can send or capture signals over distance. Proper placement and tuning are also crucial, as obstacles or incorrect alignment can weaken the signal or cause interference.

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1.2.1 Antenna Parameters:

- **Radiation Pattern:**

❖ An antenna's radiation pattern illustrates how it distributes energy when transmitting or receiving signals in various directions. This pattern essentially maps out the strength of the signal at different angles around the antenna, providing insight into how the antenna interacts with its surroundings.

❖ To make these patterns easier to interpret, engineers often use two-dimensional or three-dimensional diagrams. A 3D representation shows the overall shape of the energy distribution, while 2D plots typically taken along horizontal and vertical planes offer a simpler view for comparison and analysis. These visualizations help identify where the antenna is most effective, as well as areas where less energy is transmitted or received. Figure 1.3 illustrates the 3D radiation patterns of a sample antenna at various frequencies.

❖ Key features of a radiation pattern include the main lobe, which points in the direction where the antenna is most efficient, and side or back lobes, which represent fewer desirable directions of energy spread. By studying these patterns, designers can select or modify antennas to best suit the needs of specific communication tasks, whether they require coverage in all directions or a focused beam.

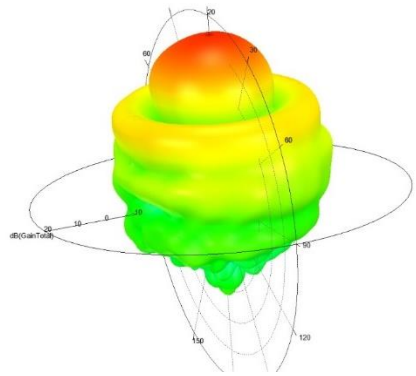


Figure 1.3: Radiation Pattern of an Antenna

- **Gain:**

❖ Gain is a key indicator of how well a reflectarray antenna can concentrate electromagnetic energy in a chosen direction, whether it is sending or receiving signals. This value shows how much more effectively the reflectarray directs power toward a specific area compared to an isotropic antenna, which spreads energy evenly in every direction. Figure 1.4 depicts the gain plot of a sample reflectarray antenna.

❖ A high gain reflectarray means that most of the input power is focused into a narrow beam, resulting in a much stronger signal where it's needed. This focused energy is achieved by carefully adjusting the phase of the reflected waves across the array's surface, so they combine constructively in the intended direction. As a result, reflectarrays can provide strong, targeted signals without the bulk of traditional parabolic dishes.

❖ This direct efficiency is especially important in fields like radar and satellite communications, where precise control over where the signal goes is essential. By maximizing gain, reflectarray antennas support reliable, long-distance links and help maintain clear, robust communication even under challenging conditions.

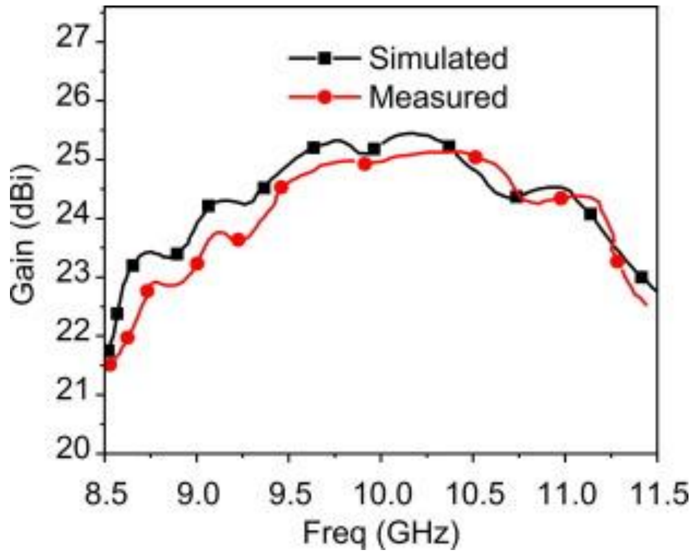


Figure 1.4: Gain Plot of Reflectarray. [Ref-1]

- **Directivity:**

❖ Directivity describes how well an antenna can concentrate its transmitted or received energy in a specific direction, rather than spreading it evenly in all directions. This property is important because it tells us how much stronger the signal will be in the intended direction compared to an antenna that

radiates equally everywhere, known as an isotropic radiator.In technical terms, directivity is calculated by comparing the intensity of radiation in the main direction of the antenna to the average intensity radiated in all directions.

- **Bandwidth:**

  Bandwidth describes the span of frequencies over which an antenna can function properly without a noticeable drop in performance. Within this frequency range, the antenna is able to efficiently send and receive signals, maintaining stable characteristics such as gain, radiation pattern, and impedance matching.

1.2.2 Types of Antennas:

- **Dipole Antenna**:

❖ A dipole antenna is a straightforward and commonly used antenna type in the field of wireless communication. It is made up of two metal rods or wires positioned in a straight line, with a small gap between them at the center where the signal is fed into the antenna. The electrical connection at the center allows current to flow in opposite directions along each rod.

❖ Dipole antennas are found in a variety of uses, including radio broadcasting, television transmission, and even in some marketing displays. Their versatility, ease of construction, and solid performance make them a go-to choice for many wireless applications.

- **Patch Antenna:**

  Patch antennas, often referred to as microstrip antennas, are designed by placing a flat metallic patch on top of a dielectric material, with a ground layer on the opposite side. The patch is usually made from a thin sheet of conductive metal, such as copper, and the entire structure is much thinner than the wavelength of the signals it is meant to handle. This design results in a lightweight compact antenna, making it ideal for devices where space is at a premium, like mobile phones, wireless communication systems, and radar equipment

- **Parabolic Reflector Antenna:**

❖ Parabolic reflector antennas, often recognized by their dish-shaped design, are highly effective for long-range communication because they can concentrate energy into a narrow, powerful beam. This is achieved by using a curved surface shaped like a parabola, which reflects electromagnetic waves from a central feed point so that they travel in parallel paths, greatly enhancing signal strength in the chosen direction.

❖ These antennas are known for their high gain and excellent conductivity, which means they can transmit and receive signals over significant distances with minimal loss. The precise shape of the dish ensures that signals are focused at the focal point, making the most efficient use of transmitted or received power.

❖ Parabolic dishes are commonly found in a variety of applications that require reliable, point-to-point communication. They are widely used for satellite links, radar systems, radio and television signal reception, and other situations where a strong, focused signal is essential. The ability to operate across a wide range of frequencies further adds to their versatility.

- **Reflectarray Antenna:**

❖ A reflectarray antenna is made up of an array of elements-either passive or active-arranged on a flat or slightly curved surface. Each element, often designed as a small patch, can be tailored to alter the phase of the incoming signal. By carefully configuring these patches, the direction in which the antenna reflects energy can be precisely controlled, allowing the beam to be steered or shaped as needed without physically moving the antenna itself.

- ❖ This type of antenna offers several advantages over traditional designs. Its lightweight and slim profile make it easy to install and integrate into various platforms, while its ability to deliver high gain and a focused beam makes it especially effective for tasks that require precise control over signal direction. These features are particularly valuable in areas such as satellite communication, radar, and any application where adaptable beam patterns are necessary.
- ❖ Reflectarray antennas can be constructed to operate with fixed beams or, if equipped with tunable elements, can dynamically adjust their coverage. This flexibility, combined with their efficient performance and straightforward design, makes reflectarrays a popular choice for modern communication systems that need reliable, high-quality signal transmission and reception.

- **Phased Array Antenna:**

- ❖ This type of antenna, known as a phased array, is built from multiple radiating elements, each of which can have its phase and amplitude individually adjusted. By changing these settings electronically, the direction of the antenna's main beam can be shifted quickly and accurately, all without needing to physically reposition the antenna. This technique, called electronic beam steering, enables the antenna to direct its signal where it's needed most or to track moving targets efficiently.

- Phased array antennas are commonly found in radar applications, wireless communication systems, and network infrastructure, where the ability to form and steer beams is essential. They are especially valuable for tasks that require rapid changes in direction, such as tracking objects or providing targeted coverage in wireless networks. Since these antennas have no moving mechanical parts, they tend to be more reliable and require less maintenance compared to traditional mechanically steered antennas.

- **Log-Periodic Antenna:**

  This type of antenna, often called a log-periodic antenna, is specifically designed to deliver reliable performance across a wide frequency spectrum. It achieves this by using several elements of different lengths, arranged in a particular pattern along a supporting boom. Each element is tuned to resonate at a specific part of the frequency range, allowing the antenna to maintain steady gain and impedance over a broad band.

- **Horn Antenna:**

  A horn antenna is well-regarded for its consistent and reliable radiation properties, particularly at higher frequencies. It is usually fed by a waveguide, which can be either rectangular or circular, that channels the electromagnetic waves into the horn structure. The flared shape of the horn provides a smooth transition for these waves from the waveguide into open space, helping to minimize signal loss and reflections. Figure 1.5 depicts a sample pyramidal horn antenna.

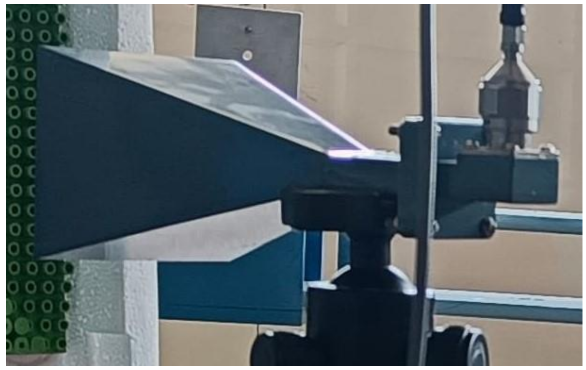


Figure1.5: Horn antenna.

- **Microstrip patch Antenna:**

  Microstrip antennas, often called patch antennas, are designed with a flat metallic patch placed on top of a grounded insulating layer. This setup results in a slim and lightweight antenna, making it especially suitable for use in devices where space is limited. The metallic patch, typically made from copper or a similar conductor, sits on one side of the substrate, while the other side is covered by a ground plane. Figure 1.6 depicts different feeding mechanisms of a microstrip antenna geometry.

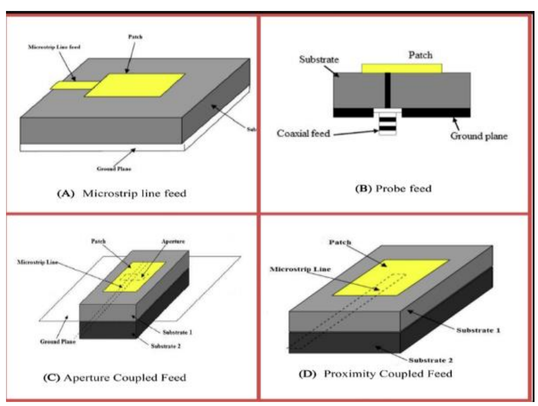


Figure 1.6: Microstrip Patch Antenna. [Ref-3]

1.2.3 Antenna Design Considerations:

- **Impedance Matching:**

❖ Impedance matching is an important consideration in antenna systems, as it helps ensure that the antenna's input impedance closely matches the impedance of the connected transmission line or receiver, which is commonly 50 ohms in many RF setups. Achieving this match is essential because it reduces the amount of signal that gets reflected back toward the source, allowing more power to be delivered to or from the antenna.

- If there is a mismatch between the antenna and the transmission line, some of the energy is reflected instead of being efficiently transferred, which can lead to weaker signals, reduced range, and even potential damage to transmitter components. The quality of the match is often indicated by the Voltage Standing Wave Ratio (VSWR); a value near 1:1 means that nearly all the power is being transferred with minimal reflection.

- **Polarization:**

  Polarization describes the orientation of the electric field in a radio wave as it travels through space. Every antenna is designed with a particular polarization in mind, such as linear, circular, or elliptical, and this characteristic plays a significant role in how effectively signals are exchanged.

- **Materials and Construction:**

  The effectiveness of an antenna is greatly affected by the materials chosen and the way it is built. Several factors come into play, including the properties of the substrate, the type of conductor used, and how well the antenna can withstand environmental conditions.

1.2.4 Antenna Deployment

- **Environment:**
  The surroundings in which an antenna operates can greatly influence how well it performs. Factors such as the lay of the land, nearby objects, and weather conditions all play a part in determining the strength and reliability of the signal.
- **Application-Specific Design:**
  Antenna design is highly dependent on the particular needs of its intended application. Different uses call for antennas with specific features, whether that's focusing energy in a certain direction, covering a wide frequency range, fitting into a compact space, or standing up to tough environmental conditions.
- **Directional Gain:**
  For tasks like point-to-point communication or radar, antennas need to concentrate their signal in a specific direction. This is achieved with types like parabolic dishes or phased arrays, which are chosen for their ability to deliver strong, focused signals over long distances.

1.3 Parabolic Reflector Antenna

Reflector antennas that use parabolic dishes to reflect incoming or outgoing radiation are called parabolic reflector antennas. Due to its high speed and high conductivity, it is suitable for satellite broadcasting, radar applications and communication. Figure. 1.7 depicts a parabolic reflector antenna.

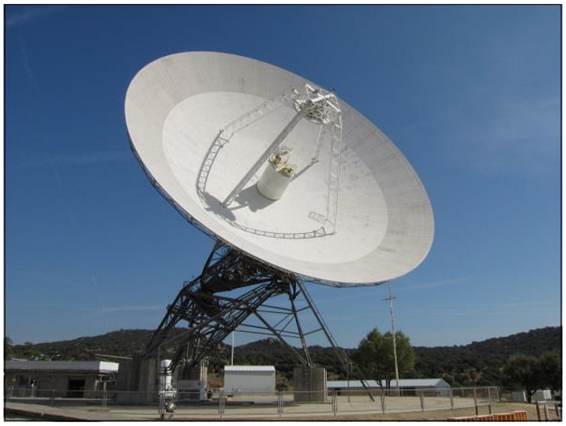


Figure 1.7: Parabolic Reflector (Ref: pngtree.com)

1.3.1 Structure and Operation

- **Dish Shape:**
  This antenna's main part is a parabolic-shaped dish that efficiently reflects electromagnetic waves. It is often made of metal or mesh.
- **Feed Element:**
  Depending on how the antenna works, the food on the target plate is responsible for sending or receiving bad electricity.
- **Focusing Properties:**
  The parabolic shape of the dish directs incoming electromagnetic waves toward the feed element, thus enhancing both amplification and directivity.

1.3.2 Advantages

- **High Gain:**
  Parabolic antennas provide the increased gain required for long-range communications. These satellite dishes focus the food's incoming wave, concentrating the energy and increasing the signal strength.

- **Directional Capability:**

  When the signal can be directed to the destination, the reliability of long-distance communication can be improved, thus reducing interference from other sources.

- **Reliability and Stability:**

  Parabolic antennas are known for their efficiency, allowing them to control the direction and direction of the signal being sent or received. This makes them ideal for satellite links and point-to-point communications.

1.3.3 Disadvantages

- **Size and Bulk:**

  Parabolic antennas are inherently large and heavy and are frequently used in satellite communications, especially at low frequencies. Operating frequency is directly related to dish size; Lower frequencies require larger antennas to achieve adequate gain.

- **Narrow Beamwidth:**

  The narrow beamwidth requires precise alignment for effective communication. Misalignment can result in significant signal loss or degradation.

- **Fixed Beam Direction:**

  The beam cannot be readily altered without relocating the entire antenna due to the fixed beam direction at the focal point of the dish. Antennas with phased arrays provide greater flexibility.

- **Complexity and Maintenance:**

  Larger parabolic antenna construction and maintenance might be challenging. For best results, installation and alignment must be done correctly, and mechanical parts like the support structures and dish mount need to be maintained on a regular basis.

- **Wind Loading:**
  Parabolic antennas are vulnerable to wind loads because of their large size and heavy weight, which can put a significant amount of force on the antenna and its supporting structures. Sturdy mounting is required to ensure stability and prevent damage.

Chapter 2

Overview of reflectarray (RA) and its Importance in antenna design:

Reflectarray (RA) antenna is a type of directional antenna that allows multiple beamforming operations through phase profile distribution by each of its single element. The technology represents a modern evolution of traditional antennas, using advanced control systems to achieve high performance and flexibility.

2.1.1 Reflectarray (RA):

Reflectarray (RA) antennas represent an advanced technology in the field of electromagnetic wave manipulation, offering highly accurate and efficient control over EM wave propagation. Compared to conventional antenna systems, reflectarrays deliver improved performance between beams, as well as greater adaptability and reduced manufacturing costs. Gaining a solid understanding of the core principles and design strategies behind reflectarray antennas is essential for leveraging their unique advantages and achieving optimal performance. Figure 1.8 depicts a sample reflectarray antenna.

Figure 2.1: Reflectarray Setup [Ref. Wikipedia]

2.1.2 Fundamentals of Reflectarray Theory:

A planar structure resembling a brain surface, composed of multiple precisely engineered elements, serves as a barrier that regulates energy input. In a reflectarray (RA), these individual units can be manipulated to control the direction of electromagnetic waves by altering the phase across the array. By modifying the power distribution, the system can be tailored to suit specific application requirements, allowing for convenient and dynamic beam steering.

- **Beam Manipulation:**

The reflective array has a flat surface covered with dispersedly arranged unit cells. Each cell is carefully designed to adjust the input power level. RA can create and direct the path of light by changing the phase of the entire array surface. With this capability, the radiation pattern may be dynamically controlled, allowing for coverage customisation and adaptive beam steering to satisfy operational needs.

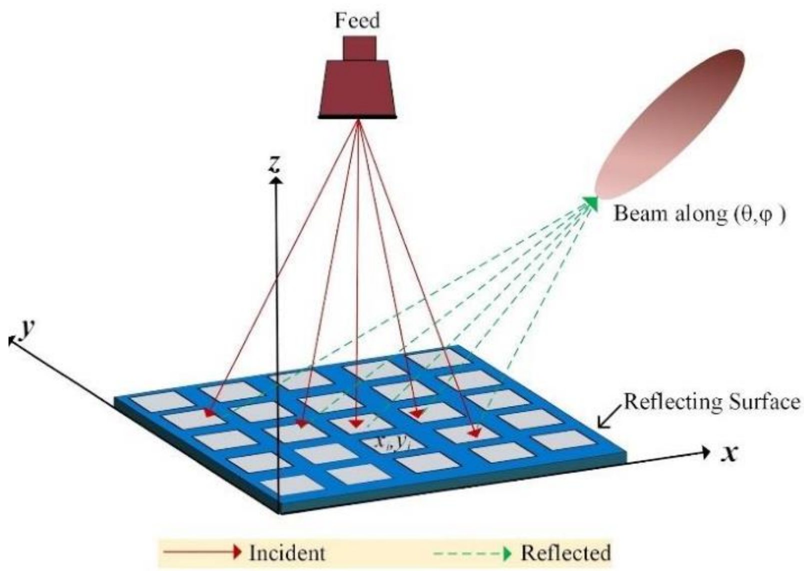


Figure 2.2: Working principal of an RA.
[Ref-4]

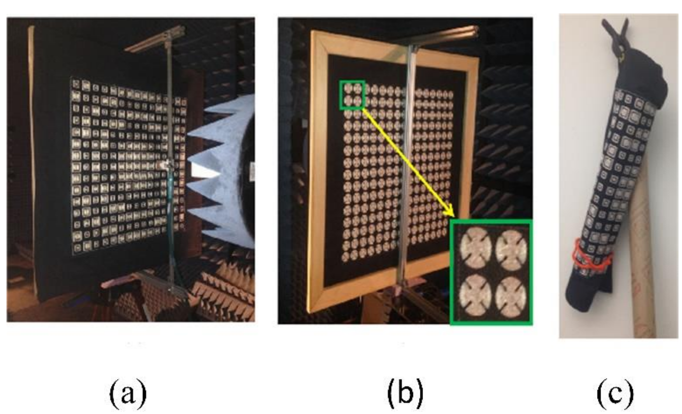


Figure 2.3: (a) Near-field of RA, (b) backside of RA, (c) rollable RA [Ref-2].

Reflectarrays can be made to conform to curved structures or non-planar surfaces by using flexible substrates and materials. Because of their intrinsic flexibility, they can be used in a variety of settings, such as conformal installations on vehicles, airplanes, or uneven surfaces where typical rigid antennas are impractical. In Figure. 2.3 an RA structure is demonstrated.

- **Cost-Effectiveness:**

  Reflectarrays lower production costs without sacrificing performance by using inexpensive materials and manufacturing methods like 3D printing or inexpensive substrates. A cheap transmitter array composed of PLA is shown in Figure.2.4. Because of their low cost, RAs are a desirable option for widespread use in satellite, consumer, and commercial communication systems.

- **Gain:**

  Gain evaluates an antenna's capacity to concentrate electromagnetic radiation in particular directions, making it a crucial performance indicator. By regulating the phase distribution along the array surface, RAs are able to attain high gain. Stronger signals in the intended directions and directed beam focusing are produced by the coherent fusion of the wavefronts from separate unit cells.

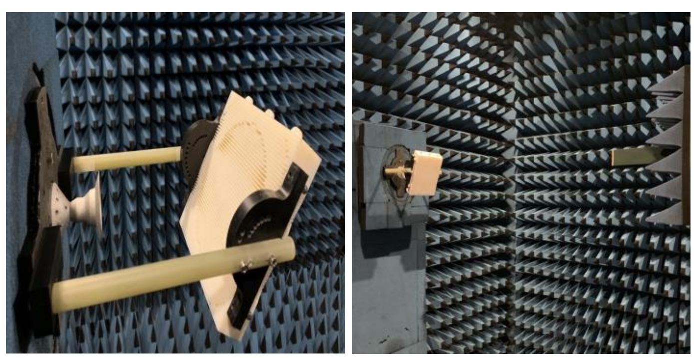


Figure. 2.4: 3-D Printed transmitarray. [Ref-6]

- **Bandwidth:**

  Large bandwidth designs enable reflectarrays to function over a large frequency range without noticeably degrading performance. Wideband RAs are flexible for multiband and multiservice applications because they can adjust to various communication protocols and signalling needs.

2.1.3 Reflectarray (RA) Technology:

Reflectarrays are made up of a number of separate radiating components arranged on a level surface. To produce constructive interference at desirable angles, each element is independently controlled to impart a certain phase shift to the incident electromagnetic wave. Because of their ability to precisely control and shape beams, reflectarrays (RAs) are a good choice for applications where dynamic control of radiation patterns is necessary. Important aspects of RA technology include of:

- **Phase Control:**

  The array elements' individual phase adjustment allows for dynamic beam control and pattern shaping, providing beamforming applications with flexibility.

- **Wideband Operation:**

  When unit cell elements are properly designed to function well across a large frequency range, reflectarrays can attain broadband performance.

- **Adaptability:**

  Because of their electronically tunable characteristics and planar construction, reflectarrays (RAs) can be applied to a wide range of communication applications, such as radar systems, wireless networks, and satellite communications.

2.1.4 Significance in Antenna Design:

Because reflectarray (RA) technology can combine the benefits of phased array antennas with the ease of use and flat profile of RA structures, it is a major player in antenna design. Compared to conventional antenna designs and parabolic reflector, RAs provide the following benefits:

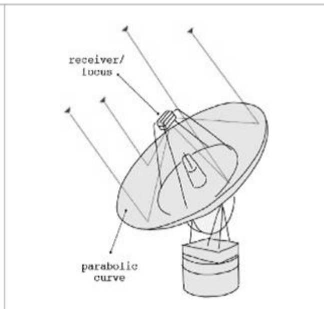
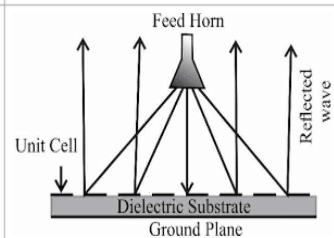
- **Directivity and High Gain:**
  The RA model is lighter and simpler than arrays, allowing to get the more advanced and ethical approach.
- **Cost Effectiveness:**
  New materials such as planar fabrication methods and 3D printing materials can produce RA cost-effectively without reducing the gain and bandwidth.
- **Modern Communication Needs:**
  Considering the continuously increasing demand of flexible and efficient antenna reflector in recent wireless communications, RA offers better alternative for efficient, effective and robust communications to be sent across multiple environments

2.1.5 Parabolic Reflector Vs Reflectarray:

RA have several advantages over parabolic reflector antennas, especially in modern communications systems where flexibility and light weight are the crucial requirement. Here are some key comparison points:

These benefits add to the RA antennas' affordability and adaptability to different wireless application, which makes them a good fit for contemporary communication systems that demand quick fixes.

Table 1: Comparison of Reflectarray and Parabolic Reflector Antennas

Parabolic Reflector	1. Conical or dish-shaped, with a curved surface that reflects and concentrates incoming signals towards the focal point. 2. Produces a fixed beam direction based on its geometry and cannot electronically steer the beam. 3. Larger and bulkier, often requiring mechanical adjustments for repositioning in certain applications.	
Reflectarray	1. Generally flat or planar, which makes it more compact and adaptable to various applications. 2. Provides electronic control of the direction and shape of the beam by adjusting the phase of individual elements, allowing for dynamic beam steering 3. Typically, smaller and lighter, making it suitable for compact and portable systems.	

Chapter 3

Literature Review

Due to their properties such as high gain, low profile and beam steering capabilities, RA antennas are in demand as a replacement for traditional parabolic and phased array antennas. RA uses a grid of unit cells to achieve a dynamic change in its position. However, challenges such as weight, cost, and flexibility affect their adoption and versatility in various applications

3.1.1 Review of Existing RA Antenna Technologies:

Several research articles have recently been published, focusing on enhancing the RA performance through innovative designs and manufacturing techniques.

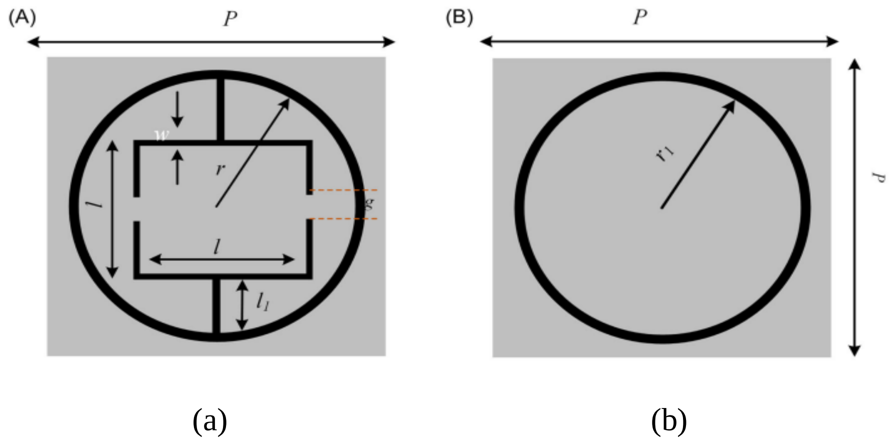


Figure 3.1: Reflectarray antenna unit cell design: (a) Top layer and (b)bottom layer [Ref-30]

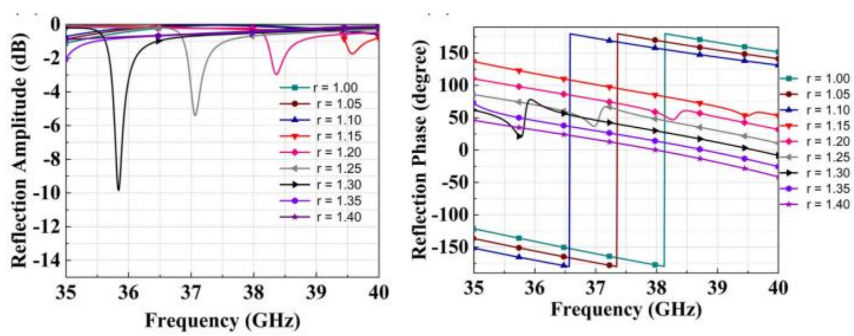


Figure 3.2: Variation of 'r' parameter and corresponding (a) amplitude response and (b) phase response. [Ref-30]

- **Novelty of the paper:**

❖ Unit cell element loss upto 0.2dB
❖ Single layer substrate is used which reduced the design complexity and fabrication cost
❖ High directive beam along the broadside direction
❖ Improved signal to noise ratio (SNR)
❖ Two discretized phase sates are obtained

- ***Limitation:***

❖ Narrow bandwidth
❖ Less angular stability
❖ Less gain
❖ Less sensitive to the position of the antenna

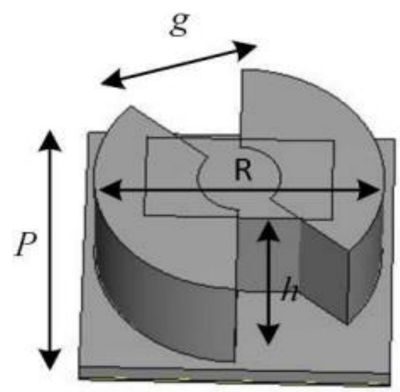


Figure3.3: Top layer of the dielectric reflectarray [Ref-19]

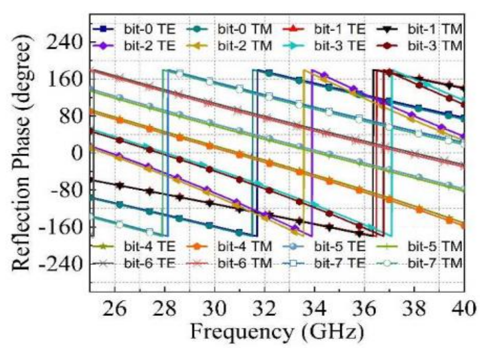


Figure3.4: frequency response [Ref-19]

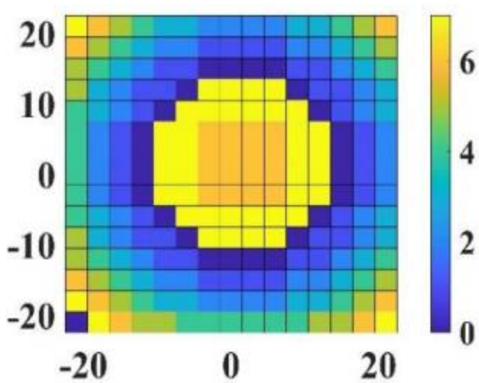


Figure 3.5: Discretized phased distribution [Ref-19]

- **Novelty of the paper**:
  - ❖ It provides eight binary states (000,001,010,011,100,101,110,111) with a phase difference of 45°
  - ❖ The low-cost design
  - ❖ Dual polarization
  - ❖ Wide band

- **Limitation:**
  - ❖ Less angular stability
  - ❖ Low gain
  - ❖ Steer the beam from ±45 deg

3.1.2 Background and Motivation:

Advancements in Reflectarray (RA) technology have sparked considerable interest, particularly for their potential applications in advanced wireless communication systems operating within the X-band frequency range (8 – 12 GHz) The wide-spread use of traditional RA designs in real-world applications is frequently hampered by issues with bandwidth, cost-effectiveness, and manufacturing. The advent of sophisticated manufacturing methods, particularly 3D printing, offers fresh chances to get around these obstacles and improve antenna performance. The goal of this research is to use 3D printing technology to create a broadband, high-gain, lightweight, affordable, and adaptable RA design. This project intends to overcome the limitations of existing RA technology and investigate new avenues for antenna design and deployment by utilizing the special powers of 3D printing.

The primary motivations for this study include:

- **Performance Enhancement:**

Exceptional performance and greater coverage of wide bandwidth operations are needed. The RA concept aims to overcome the performance limitations of phased array (TA) and traditional parabolic reflectors through the design and development of cell models.

- **Cost Effectiveness:**
  By using simple and inexpensive materials such as copper tape and ABS filament, production costs can be significantly reduced compared to traditional manufacturing techniques. These techniques allow payments to be made without interfering with the antenna.
- **Adaptability and Flexibility:**
  Design properties such as lightweight, flexible and easy-to-deploy antenna designs for a variety of applications. Complex geometries and designs can be realized to suit different needs using 3D printing technology.

By addressing these limitations, this study aims to open the door to efficient, affordable, and versatile RA reflectors that can be best used in communication applications. In the X-band frequency range, the RA design is intended to demonstrate the ability to create strong and reliable communications across multiple locations and distances.

Chapter 4

Research Objectives and Scope:

The main target of the research and study of this study, which aims to use 3D printing technology to improve the design, production and performance quality of the RA antenna, is the X-band frequency range. The main objectives of this study are listed below:

- **Design Optimization:**
  Optimizes unit configurations across the frequency range from (8 GHz to 12 GHz) to create revolutionary RA designs with enhanced performance such as gain, directivity and wide coverage.
- **Performance Assessment:**
  In depth and extensive simulations and measurements are to be performed to evaluate the effectiveness of the RA design. Parameters such as tuning phase, reflection coefficient, bandwidth and gain are designed to indicate the quality of the reflectarray antenna.
- **Cost Effective Manufacturing:**
  To find out whether 3-D printing can be used to manufacture RA antenna, researchers are studying to investigate heavy duty materials such as copper tape and ABS filament, which can be made at a lower cost without sacrificing performance standards required for a particular application.
- **Flexibility and Versatility:**
  To evaluate the suitability, reliability and adaptability of the RA design to various deployment scenario, it is necessary to consider how the reflectarray can be folded or configured to meet specific operating needs. This makes the reflectarray ideal for applications requiring portability or customizable configuration.

  The scope of this research includes the following crucial aspects:
- **Unit Cell Optimization:**
  Detailed analysis and optimization of unit cell configurations in order to achieve better desired gain performance and wideband operation bandwidth.
- **Simulation and Measurement:**
  Implementation of advanced simulation tools such as HFSS and variety of measurement techniques to validate and improve the performance of the proposed RA design.

- **Material Selection and Manufacturing:**
  Examination of suitable materials such as ABS and manufacturing methods with a focus on 3D printing technology for cost-effective and flexible antenna production, which are crucial in order to make the RA compatible.
- **Deployment Scenarios:**
  Exploration of practical deployment scenarios where the RA design can be applied to highlight its versatility, flexibility and adaptability in modern communication systems.

4.1.1 Summary of Research Contributions and Innovations:

This research has achieved significant and remarkable improvements and achievements in RA design and fabrication by using 3D printing to realize the concept of lightweight, low-cost, flexible, wideband and high-gain RA in the X-band frequency range of (8GHz to 12 GHz)

4.1.2 Research Contributions:

- **Proposed RA Design:**
  A new reflectarray (RA) has been designed for 8 to 12 GHz in X-band frequency, suitable for high gain, wideband, and versatile applications.
- **Enhanced Performance:**
  Improve unit cell design and use cutting-edge technology for greater and broader benefits.

- **Cost Effective Manufacturing:**

  Exploring the possibility of using 3D printing to save on production costs while maintaining high performance using light and cheap materials such as copper tape and ABS

- **Flexibility and Adaptability:**

  Create a thin, flexible RA framework that can be quickly implemented and adapted to a variety of applications such as providing flexibility for daily communication.

4.1.3 Research Innovations:

- **Advanced Unit Cell Optimization**:

  Take advantage of the latest cell topologies to maintain cost-effective systems while increasing antenna flexibility, high gain, efficiency and bandwidth.
- **Integration of 3D Printing Technology**:

  Use the special features of 3D printers to create simpler and lighter substrate of RA.
- **Performance Validation:**

  Validating the performance of the proposed RA reflector through extensive simulation and testing will demonstrate its usefulness in real-world applications.
- **Practical Deployment Scenarios**:

  Explore real world deployments to demonstrate the flexibility of the RA model for different practical situation and its ability to solve today's communications challenge.

Chapter 5

Designing Reflectarray with 3-D Printing Technology

The strategy introduced in this research directly tackles the limitations found in conventional Reflectarray (RA) antenna designs. The newly proposed RA architecture is developed to enhance manufacturability, increase link bandwidth, and provide improved sensor support when compared to current technologies. This design focuses on achieving superior performance across a broad frequency range by carefully optimizing the antenna structure.

To ensure cost-effectiveness, the design utilizes affordable materials like ABS, which helps lower production expenses relative to traditional fabrication techniques. Additionally, integrating 3D printing technology into the manufacturing process allows the antenna to be more flexible, making it easier to store and adapt to different configurations as needed.

5.1 Unit cell Design:

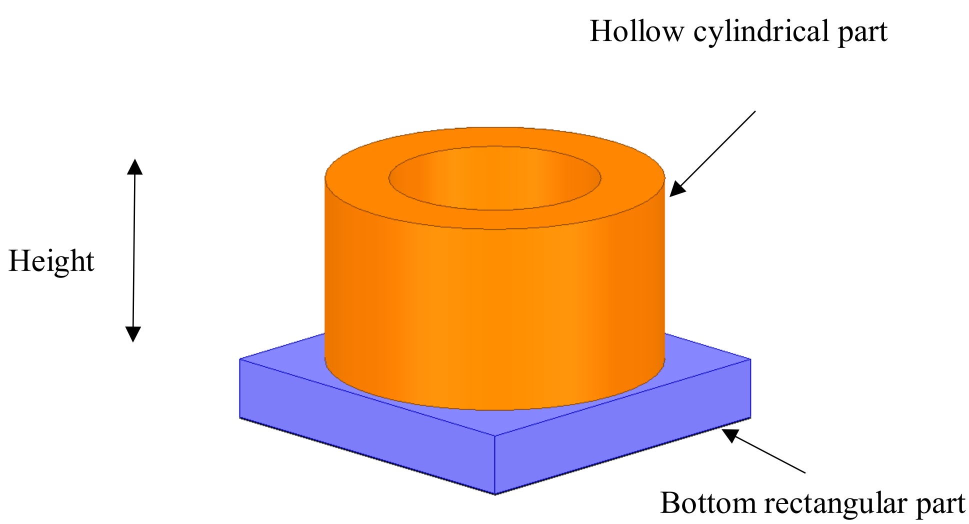


Figure 5.1: Unit cell design: dimetric view

The unit cell design presented is characterized by a hollow cylindrical pattern on the top of a dielectric substrate. Two layers of dielectric substrates are used; the top and bottom are made of ABS-material (dielectric constant = 3.2 and loss tangent = 0.002) .The unit cell has a periodicity (p) of 8.5 mm, and Substrate (bottom rectangular part) thickness: 1.6mm

A distinctive feature of this unit cell is the realization of a broad reflection phase range of 360^{o}, while varying the inner and outer radius and height of the hollow cylinder part, thickness and the width of the bottom substrate have been kept constant as shown in Figure 5.1. thereby ensuring reliable phase performance.

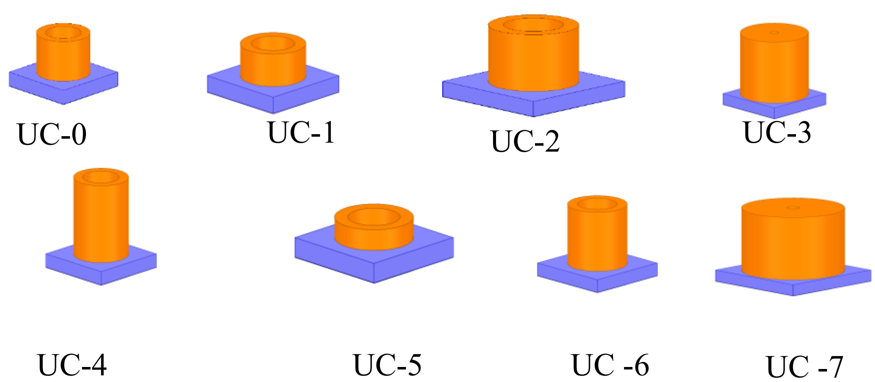


Figure.5.2: Unit cell configurations for different phase values

UNIT CELLS	UC-0	UC-1	UC-2	UC-3	UC-4	UC-5	UC-6	UC-7
Rmin (mm)	2	2	2	2	2	0.5	2	1.5
Rout (mm)	3	3	3	3	3	4	3	4
H (mm)	4.56	3.18	5.95	1.7	7.46	9	9.15	8.5
PHASE	0°	45°	-45°	90°	-90°	135°	-135°	180°

Table 2: Design parameters

The unit cell design achieves a high reflection magnitude of 0.01 dB across the frequency spectrum spanning from 8 GHz to 12 GHz. The reflection amplitude remains small for a frequency range of 8 to 12 GHz, while varying the Rin Rout and H. The corresponding phase, however, varies from +180^o to -180^o,

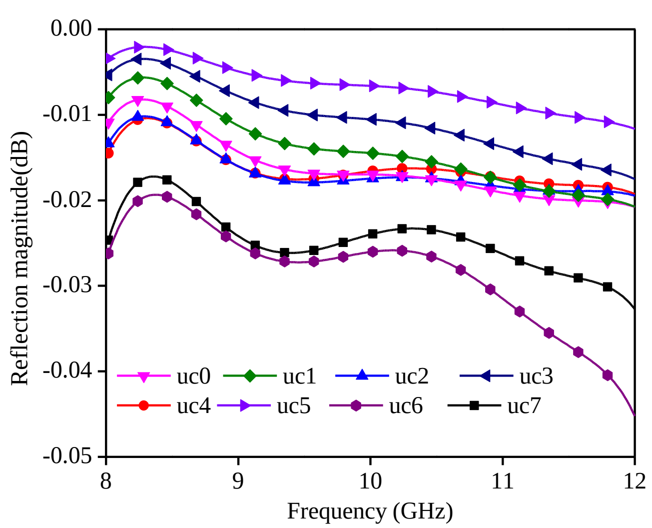


Figure 5.3: Amplitude Response of unit cells Vs Frequence

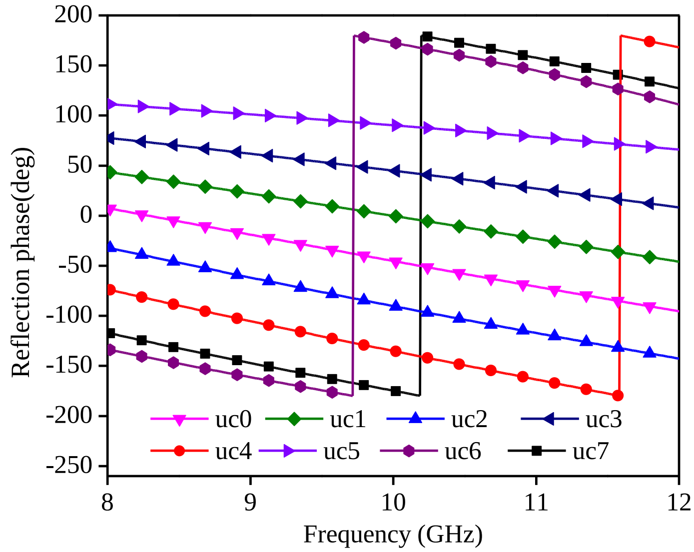


Figure 5.4: Phase Response of unit cells Vs Frequence

5.2 Reflectarray Design:

The RA design process follows a systematic methodology to determine the phase profile, translate it into a practical layout, and optimize performance for specific operational requirements. Figure. 2.5 illustrates the mathematical equation behind the reflectarray design.

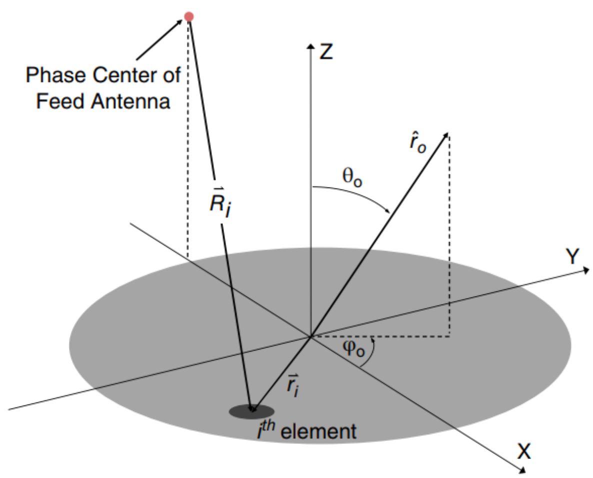


Figure 5.5: Typical geometrical parameters of a planar reflectarray antenna. [Ref - 34]

5.2.1 Profile Phase Determination:

$$\phi_i = k_0 \times \left(R_i - \sin(\theta_0) \times (x_i \cos(\varphi_0) + y_i \sin(\varphi_0))\right) - - - (1)$$

Here, k_0 represents the wave number, θ_o and ϕ_o denote the elevation and azimuth angles of the reflected beam direction, x_i and y_i are the coordinates of the r_{th} unit cell (positioned in the xy plane at z = 0), R_i signifies the distance between the i_{th} unit cell and the feed antenna position, and ϕ_i represents the phase angle of the i_{th} unit cell.

5.2.2 Quantization for Practical Realization:

Though the above equation generates a continuous phase distribution for all 144-unit cells, practical limitations in resolution and fabrication complexity make it challenging to realize such a large number of variant unit cells. To address this challenge, the continuous phase profile of 360° is discretized into 8 distinct phases with a phase difference of 45° between successive phase profiles. This quantized phase profiles guide the generation of corresponding unit cells by adjusting their geometric dimensions. The quantized values can be obtained as following:

$$\mathrm{I} = \mathrm{round}\ \frac{(\mathrm{X} - \mathrm{X_{min}})}{\Delta}$$

$$\Delta = \frac{(\mathrm{X_{max}} - \mathrm{X_{min}})}{\mathrm{L}}$$

$$\mathrm{L} = 2^{\mathrm{n}}$$

$$\mathrm{Xq} = \mathrm{X_{min}} - (\mathrm{I} \times \Delta)$$

Where $\mathrm{X_{max}}$ & $\mathrm{X_{min}}$ are the maximum and minimum phase values, Δ is the step size, L is the number of levels.

5.2.3 Unit-Cell Placement and Simulation:

After determining the quantized phase profiles, their corresponding unit cells have been placed in the RA aperture, such that the desired phase distribution is obtained over the whole structure.

5.3 Methodology for Reflectarray Design:

To optimize the performance of RAs, a systematic approach has been considered to fine-tune unit-cell parameters, control phase distribution, and configure the array layout for precise beam steering and gain enhancement.

5.3.1 Unit-Cell Optimization:

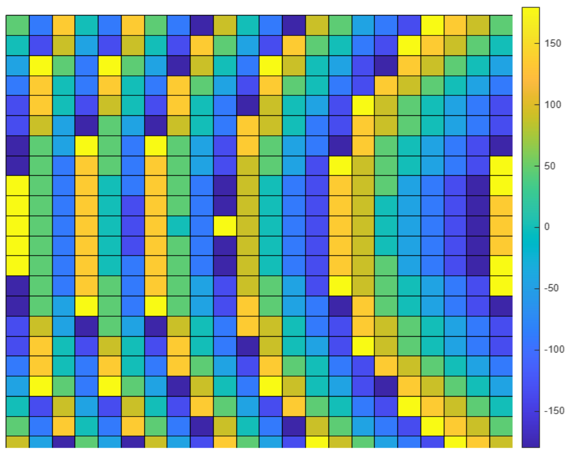
During the initial stage of the project, unit cell dimensions were carefully chosen to correspond with the desired frequency range of operation. Ansys High Frequency Structure Simulator (HFSS) was employed to iteratively fine-tune these parameters. This process aimed to obtain targeted phase shifts exceeding 55 degrees, achieve particular reflection coefficient values, and ensure the necessary conditions for robust beam steering and control.

5.3.2 Array Layout and Configuration:

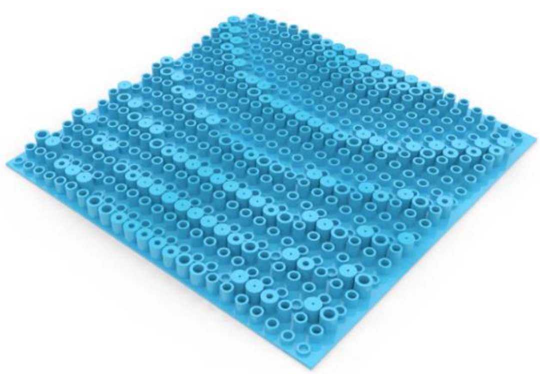
The configuration and positioning of the unit cells within the reflectarray have been meticulously determined based on the required phase distribution. This design process focuses on creating layouts that fulfill the targeted goals for beam steering and improved gain, ensuring that the spatial arrangement of the array contributes to the intended antenna performance.

5.3.3 Phase Distribution Analysis and Quantization:

After evaluating the desired stage profile, the continuous stage distribution has been converted into discrete states through quantization. This quantization process makes the design practical for fabrication while maintaining its beam steering capabilities.



(a)



(b)

Figure 5.6: (a)Quantized Phase Profile (b) Designed RA using HFSS

5.3.4 Scripting and Simulation:

To automate unit-cell placement based on our optimized designs, Python scripts are developed. These scripts have allowed us to precisely position unit cells in the RA aperture, ensuring significant gain enhancement and accurate beam control

5.4 Simulations:

The simulation of the RA design provides crucial insights into its performance and beam steering capabilities under specific operational scenarios. In Figure. 5.7 the setup used for simulation is illustrated.

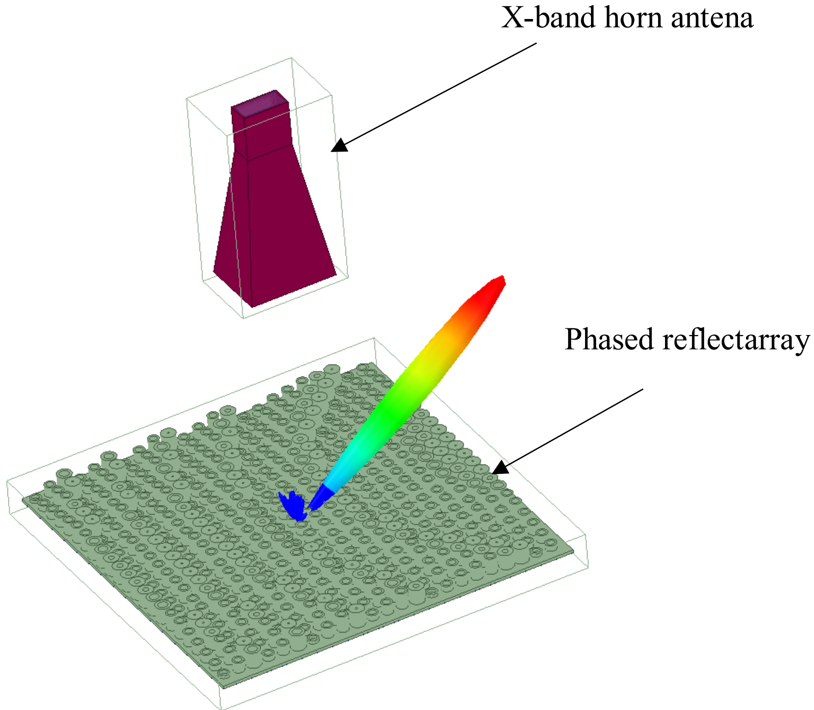


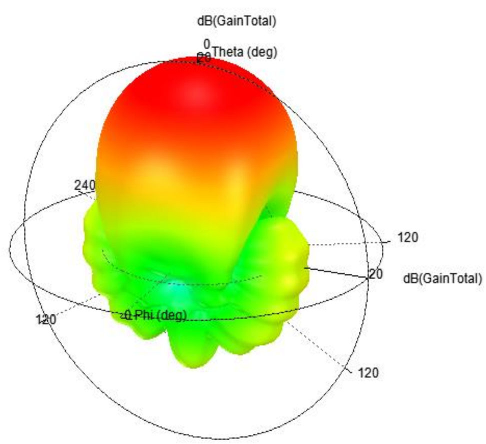
Figure 5.7: simulation setup.

5.4.1 Simulation Setup Details:

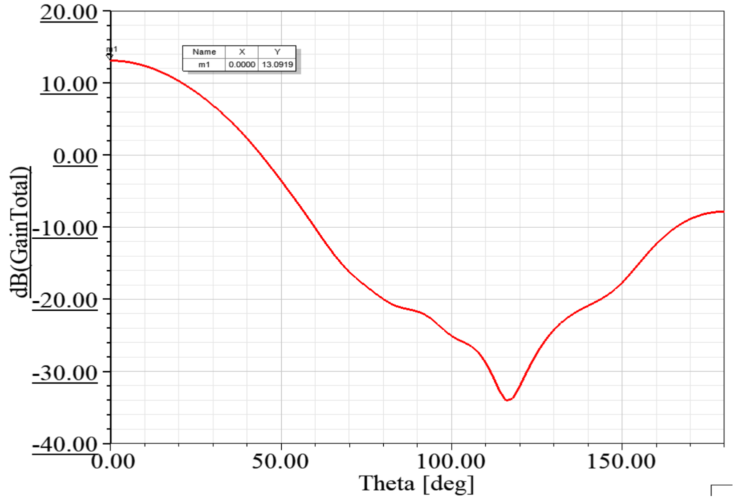
The simulation setup utilizes a finite element boundary integral (FEBI) environment to model the complete RA and one horn antennas. A standard gain X-band horn antenna, designed according to the WR90 model specifications, serves as the transmitting antenna, and is kept in the near field of the RA structure. The distance and position of the RA with respect to this transmitting antenna precisely decides the phase profile of unit cells at different coordinates, and corresponding unit cells. On the other hand, a receiving horn antenna of similar type (X-band WR90 model) has been placed at a far-field location. The line of sight between the RA structure and the receiving antenna is maintained based on the beam directing capability of the proposed design. Since the proposed RA is designed to bend the reflected signal at 55°angle, the angle between the transmitting, RA structure, and receiving antennas are maintained 55°.

5.4.2 X-band horn antenna Simulation:

Standard gain horn antennas operating in the X-band frequency range (8–12GHz) and using the WR90 waveguide are popular choices for reference measurements due to their reliable and well-characterized performance. In this we get an gain 13.09dB



(a)



(b)

Figure 5.8: (a)3D radiation pattern (b) 2D radiation Pattern of standard X-band horn antenna

5.4.3 Reflectarray Simulation:

The RA structure is then placed while keeping both antennas constant, and the full-wave simulation has been carried out. During simulation, notable improvements and performance enhancements are observed:

- **Significant Gain Enhancement:**

Compared to the copper plate simulation, the RA design yields a substantial gain enhancement. The reflected beam is more tightly focused and directed towards the receiving antenna, enhancing signal strength and reception quality.

- **Precise Beam Bending:**

The RA effectively bends the radiated beam at the specified 55^{o} angle, demonstrating its capability to dynamically steer the beam direction. The 2-D and 3-D radiation pattern responses of the RA structure are depicted in Figure 2.9 and Figure2.10

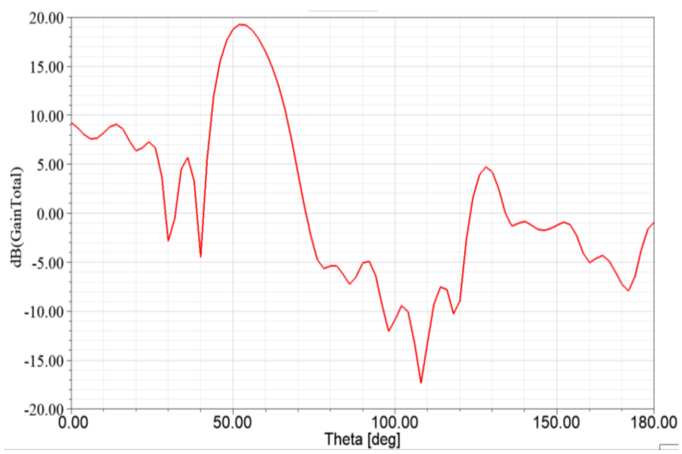


Figure 5.9: 2-D Radiation pattern of the designed RA at 10 GHz

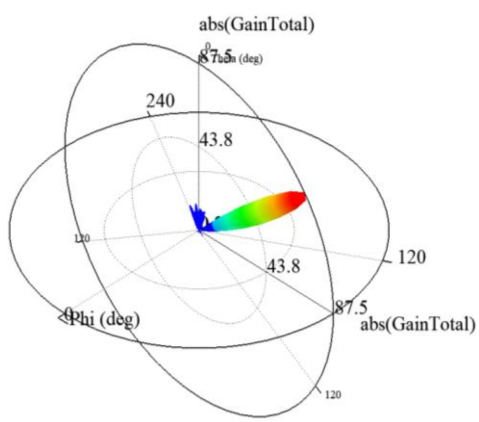


Figure 5.10: 3-D Radiation pattern of the designed RA at 10 GHz

5.4.4 Practical Implications:

The simulation results validate the effectiveness and functionality of the RA design in real-world scenarios:

- **Beam Steering:**

  The RAs ability to dynamically steer the beam opens up possibilities for adaptive and agile communication systems, optimizing signal coverage and quality.

- **Enhanced Performance:**

  By achieving significant gain enhancement, the RA design enhances the overall performance of antenna systems, improving communication reliability and range.

5.5 Fabrication:

The fabrication process as shown in Figure. 5.11 involves integrating advanced 3-D printing techniques with carefully selected materials to achieve lightweight, flexible, and cost-effective antenna construction. The detailed fabrication steps are mentioned below:

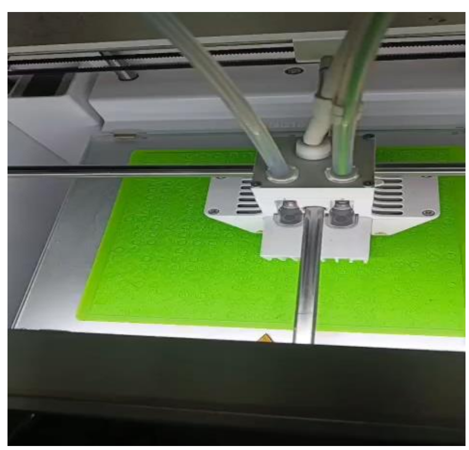


Figure 5.11: Fabrication process of reflectarray.

- **Material Compatibility:**
  Based on 3-D printer compatibility, a few materials have initially been selected, like PLA, ABS, Teflon, etc., and among them, ABS has been finalized based on full-wave simulation results and commercial availability.
- **Dielectric Constant Consideration:**

  ABS material has a dielectric constant of 3.2 and loss tangent

  of 0.002. although a lower loss tangent value is preferred for antenna fabrication, but, due to limited availability of 3-D printer compatible filaments, ABS material has been chosen.

5.5.1 3D Printing Technology:

- **Layer-by-Layer Fabrication:**
  Once the basic structure and printing filaments are finalized, the dielectric layers have been fabricated using 3-D printing technique. Important specifications used during the printing process are: build plate temperature: 60^o, nozzle temperature: 210^o, printing speed: 100%, infill density: 100%, and nozzle diameter: 2.85 mm. With these settings, each ABS layer (top and bottom) has taken 14-18 hours for completion of the printing.

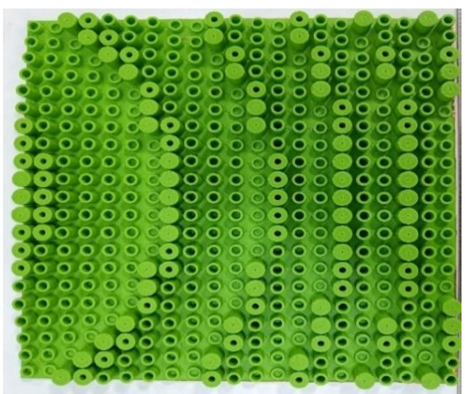


Figure 5.12: Fabricated Reflectarray

5.5.2 Pasting of Copper Tape:

At the end stage, copper tapes are cut from a reel in the form of square loops or patches, using a Vinyl cutter, and pasted on the backside of the fabricated Reflectarray

Chapter 6

MEASUREMENT

6.1.1 Measurement Setup:

The experimental setup for evaluating the performance of the RA design involves precise measurements conducted, utilizing specialized equipment to assess antenna characteristics and beam manipulation capabilities. The measurement setup is used depicted in Figure. 6.1

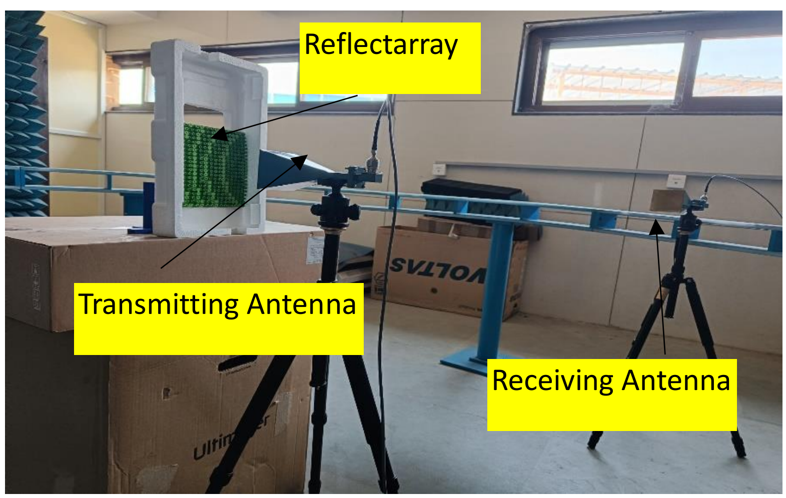


Figure 6.1: Measurement Setup

6.1.2 Associated Equipment:

The measurement setup consists of following equipment, as below:

- **Transmitter Antenna:**

  A X-band transmitting horn antenna (operating range: 8-12 GHz) has been positioned in the near field directly facing the structure at a distance of 150 mm. The incident angle of EM wave from this transmitting antenna is thus maintained at 0^{o}.

- **Receiving Antenna:**

  The receiving antenna has been placed in the far field at 55^{o} angle relative to the RA surface. This angle has been determined during full-wave simulation, and corresponding RA structure has been fabricated.

- **Vector Network Analyzer (VNA):**

  The experimental setup utilizes one VNA from Anritsu (S802E) equipped with high-frequency capabilities to assess antenna performance. The VNA has been connected to both transmitting and receiving antennas for data acquisition

6.1.3 Data Acquisition and Analysis

The VNA facilitates the acquisition of comprehensive data sets, capturing key antenna parameters such as reflection magnitude, phase tuning, gain enhancement, and beam steering characteristics across the operational frequency range (8 – 12 GHz). This data forms the basis for evaluating the performance of the fabricated RA design under various operating conditions. A frequency sweep of 0.1 GHz and an intermediate frequency (IF) bandwidth of 50 Hz have been reached during the experiment in order to precisely record the measurement data.

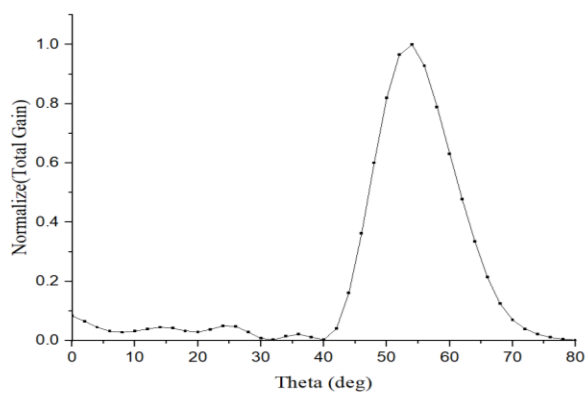
6.1.4 Measurement Results:

- **High Gain:**

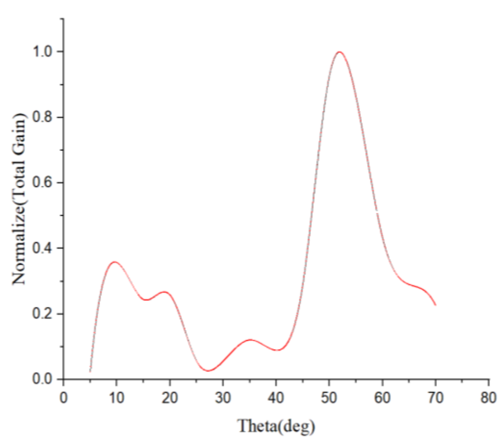
RA achieved a gain of 19.50 dB as depicted in Figure. 2.9 compared to design; This indicates a significant improvement in signal strength in the desired direction. This advancement requires the creation of strong and reliable communication across multiple functions and distances.

- **Wide Bandwidth:**

The highest gain occurs at the center frequency, ensuring broad coverage across the X-band spectrum



(a)



(b)

Figure 6.2: (a)Measured gain , (b)simulated gain

Chapter 7

Conclusion and Future Scopes

7.1.1 Conclusion:

- 6.5dB gain enhancement
- beam steering at 55º angle
- Utilized a cost-effective and flexible approach by employing lightweight material and 3D printing techniques, effectively reducing manufacturing costs while preserving high performance
- minimize loss
- Wide phase tuning (~ 360º)
- Increase the beam steering angle without losing the gain

Table 2: Comparative overview between recent research findings and the specific achievements of this project:

Ref	Size	Frequency (GHz)	Maximum Gain	Fabrication Technique	Cost
7	$30\lambda_0 \times 30\lambda_0$	9.2 – 10.4	25.4	PCB	Medium
8	$15\lambda_0 \times 15\lambda_0$	26 – 35	29.4	3-D Printing	Low
9	$9.7\lambda_0 \times 9.7\lambda_0$	26 - 29	23.4	PCB	Medium
10	$14\lambda_0 \times 14\lambda_0$	27.5 – 28.7	30.5	PCB	Medium
11	$5.3\lambda_0 \times 5.3\lambda_0$	37 - 39	19.1	PCB	Medium
This Work	**$2.84\lambda_0 \times 2.84\lambda_0$**	**8 – 12**	**19.50**	**3-D Printing**	**Low**

7.1.2 Future Score:

The proposed RA structure has been designed and develop with a primary aim to realize the concept on 3-D printing technique. Although the proposed method exhibits significant improvement, several research works can be considered as a part of future scope:

• Integration with Active Components:

The proposed RA design is a passive structure, and can re-direct the beam at a particular direction only (55 deg in the proposed design). However, the beam should be re-directed at different angles for diverse applications. Hence, a reconfigurable RA can be realized as a future scope. The main challenge in realizing a reconfigurable RA on 3-D printing technique will be a major challenge.

• Conformal Analysis:

Although the proposed structure has been made on flexible ABS material, its conformal analysis has not been carried out. A detailed analysis should be executed to get an idea on upto what angle the structure can be conformed to still obtain a beam bending response.

• Material Exploration:

Since 3-D printer has a limited material choice of filaments, hybrid fabrication facilities will be explored along with alternative material search to further enhance the mechanical strength, thermal stability, and other important parameters while realizing the RA structure.

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