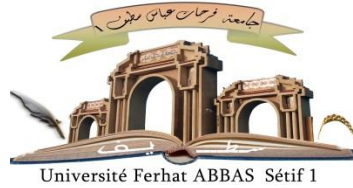


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**Design of waveguide-fed profiled smooth conical horn
associated with dielectric lens antenna for sub-THz
application**

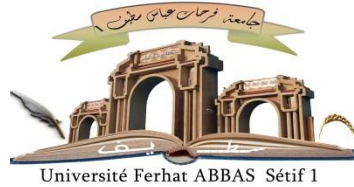
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Par

MENNANI Zinedine

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Abstract

This thesis explores the conception, design, and analysis of a high-performance integrated antenna system tailored for sub-terahertz applications. The proposed structure combines a Waveguide-Fed Profiled Smooth Conical Horn (WFPSCH) with an Extended Dielectric Lens Antenna (DLA), capitalizing on the complementary electromagnetic properties of both elements to achieve enhanced radiation performance.

The horn antenna functions as an efficient primary radiator, offering low-loss excitation and stable polarization, while the dielectric lens serves to improve beam collimation, directivity, and aperture efficiency. This integrated configuration enables the mitigation of typical limitations associated with standalone horn or lens antennas, particularly in terms of beam shaping, sidelobe suppression, and spatial resolution.

The antenna system was rigorously designed and optimized using CST Microwave Studio 2024, ensuring high simulation accuracy across the operating frequency range. The results demonstrate that the combined antenna achieves significant performance gains, including high directivity, excellent beam symmetry, and low sidelobe levels. At an operating frequency of 240 GHz, the antenna exhibits a peak gain of 36.3 dBi, with a compact overall dimension of $28.77 \times 28.77 \times 37.26 \text{ mm}^3$.

This work highlights the viability of hybrid horn-lens antenna architectures for advanced millimeter-wave and sub-THz systems, offering promising potential for applications in high-speed wireless communication, radar sensing, and terahertz imaging technologies. The proposed design strikes an effective balance between performance, compactness, and fabrication feasibility, contributing to the ongoing development of next-generation high-frequency antenna systems.

Keywords: Waveguide-Fed Profiled Smooth Conical Horn, Dielectric Lens, directivity, beamwidth, sidelobe, polarization, radiation, millimeter-wave, radar, imaging technologies.

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Dedication

I dedicated this modest work

to the memory of my beloved parents

**To my beloved wife and children, for their endless patience, encouragement, and
understanding throughout this challenging endeavor.**

**To my brothers and sisters, whose love, support, and encouragement have always
given me strength.**

To my entire family, whose belief in me has been my guiding light.

This work is for them, with all my love and gratitude.

List of Abbreviations

WFPSCH Waveguide-Fed Profiled Smooth Conical Horn

CST Computer Simulation Technology

IOT Internet of Things

RF Radio Frequency

HPBW Half-Power Beamwidth

FNBW First-Null Beamwidth

RHCP Right-Hand Circular Polarization

LHCP Left-Hand Circular Polarization

VSWR Voltage Standing Wave Ratio

EM Electro-Magnetic

MIMO Multiple Input Multiple Output

MPA Micro-strip Patch Antenna

TE Transverse Electric

TM Transverse Magnetic

PTFE Polytetrafluoroethylene

SWCHA Smooth-Well Conical Horn Antenna

FDTD Finite-Difference Time Domain

FEM Finite Element Method

MoM Method of Moments

RCS Radar Cross Section

NFC Near-Field Communication

MEMS Microelectromechanical System

PCB Printed Circuit Board

SDR Software Defined Radio

General introduction

The rapid evolution of communication technologies and the ever-increasing demand for faster, more reliable data transmission have placed antennas at the core of modern wireless communication systems. Antennas serve as critical interfaces between electromagnetic waves and the devices that rely on these signals, making their design and performance essential for the success of a wide range of applications, including mobile networks, satellite communications, radar systems, and emerging technologies like 5G and the Internet of Things (IoT) [1]. This thesis explores the state-of-the-art advancements in antenna technology, with a particular focus on the design and integration of innovative antenna solutions to meet the challenges of next-generation communication systems.

The first chapter provides a comprehensive overview of the fundamental principles of antenna design, the key parameters that define antenna performance, and the various types of antennas used in modern communication systems [2]. It highlights the evolution of antenna technologies, from simple dipoles to advanced structures designed for high-frequency applications, including millimeter-wave and sub-THz communications. The chapter also explores the current state of the art in antenna research, emphasizing the ongoing developments in materials, fabrication techniques, and design methodologies that are enabling the next generation of communication systems [3], [4].

The second chapter delves into the design principles of horn antennas, a widely used type of antenna known for its high gain and directivity [5]. Horn antennas, with their simple structure and efficient radiation characteristics, are integral to various applications such as radar, satellite communication, and antenna measurement systems[6]. This chapter explores the different types of horn antennas, including rectangular, pyramidal, and conical horn designs, and discusses their performance characteristics, design considerations, and practical applications. The chapter also highlights the advantages of horn antennas in terms of their ability to provide broad bandwidth and stable radiation patterns [7].

The third chapter focuses on the integration of dielectric lens antennas, a promising solution for improving antenna performance in terms of gain, directivity, and efficiency. Dielectric lenses allow for the concentration of electromagnetic waves into highly directional beams, making them ideal for high-frequency applications such as radar, satellite communications, and millimeter-wave systems. The chapter examines the principles of dielectric lens design, including material selection, geometric configuration, and fabrication

methods. It also explores the benefits and challenges of integrating dielectric lenses into antenna systems, as well as the latest advancements in the field [8].

The final chapter presents a novel antenna design approach that combines a waveguide-fed profiled smooth conical horn with a dielectric lens antenna for sub-THz applications. This hybrid design aims to overcome the challenges associated with high-frequency communications, such as signal attenuation, bandwidth limitations, and the need for high gain and directivity [6]. The chapter explores the design principles behind this integrated approach, detailing the advantages of waveguide feeding and the optimization of horn profile shapes to improve radiation patterns. It also discusses the potential applications of this antenna design in the sub-THz range, which is critical for future communication systems and emerging technologies [9].

Together, these chapters provide a thorough examination of antenna technologies, focusing on the design, integration, and optimization of advanced antenna systems that will drive the performance of next-generation wireless communication systems. Through a detailed analysis of horn and dielectric lens antennas, along with an innovative approach to sub-THz antenna design, this thesis aims to contribute to the ongoing advancement of antenna technologies for the future of high-speed, low-latency communications [10], [11].

Chapter 1. Antenna Generalities

1.1. Introduction

The continuous evolution of communication systems relies significantly on the development of efficient and reliable antennas. Antennas serve as a critical interface between wireless communication devices and the electromagnetic spectrum, enabling the transmission and reception of radio frequency (RF) signals [1]. In modern systems, applications across mobile networks (4G, 5G) to satellite communication, radar systems, and the emerging Internet of Things (IoT) demand sophisticated antenna solutions to achieve high performance in terms of gain, directivity, bandwidth, and efficiency [12], [13].

The growing need for high-speed, low-latency communication, particularly in 5G and beyond, has accelerated the development of advanced antenna technologies capable of supporting beamforming and massive MIMO (Multiple Input Multiple Output) systems [14]. Beamforming antennas focus signal energy in targeted directions, greatly enhancing link reliability and spectral efficiency [12]. In contrast, traditional omnidirectional antennas distribute energy uniformly, resulting in increased path losses and reduced coverage. Massive MIMO leverages large antenna arrays to boost spatial multiplexing, allowing simultaneous connections with multiple users and significantly enhancing overall network capacity [15], [16].

Furthermore, as the communication landscape transitions to millimeter-wave (mmWave) frequencies, designing compact and efficient antennas presents significant challenges due to higher propagation losses and more stringent design constraints. mmWave antennas must provide precise directivity and high gain to mitigate atmospheric attenuation and ensure adequate signal coverage [17]. To address these requirements, advanced techniques such as array configurations, metamaterials, and dielectric lenses are increasingly being investigated [9], [18].

1.2. Antenna Overview

1.2.1. Definition

Antenna is a device used to radiate or receive electromagnetic waves, typically in the radio frequency (RF) spectrum. It acts as a transducer that converts electrical energy into

electromagnetic radiation, enabling the transmission of signals through space. when transmitting, and vice versa when receiving [1]. Antennas play a crucial role in various communication systems, enabling wireless transmission and reception of signals over long distances [6].

More specifically, antennas are designed to match the impedance of the transmitter or receiver to that of free space, facilitating the efficient transfer of energy. They are characterized by their radiation pattern, gain, directivity, polarization, and bandwidth, which all influence the performance and efficiency of the communication system [1], [10].

1.2.2. History of Antennas

The history of antennas traces back to the late 19th century, starting with James Clerk Maxwell's groundbreaking work in the 1860s that laid the foundation for understanding electromagnetic radiation. In 1888, Heinrich Hertz demonstrated the reality of electromagnetic waves through experiments, proving that energy could travel through space. The first practical application of antennas arrived in the early 1900s when Guglielmo Marconi used a dipole antenna to send radio signals across the Atlantic. In the 1920s and 1930s, new antenna designs like directional and parabolic antennas were introduced, greatly improving the range and precision of radio transmissions. World War II spurred rapid advancements in antenna technology, particularly for radar systems, leading to the creation of phased-array and parabolic dish antennas. The 1960s and 1970s marked the rise of satellite communications, with parabolic antennas becoming crucial for receiving signals from geostationary satellites [19]. By the 1980s and 1990s, the development of mobile phones drove the miniaturization of antennas, and new wireless technologies like Wi-Fi and Bluetooth demanded more compact, efficient designs. Today, modern communication systems like 4G, 5G, and the Internet of Things (IoT) depend on advanced antenna technologies such as massive MIMO and phased arrays. Looking ahead, the future of antennas focuses on integrating cutting-edge materials and innovations to achieve even faster speeds, broader connectivity, and more efficient wireless systems [14], [12].

1.3. Fundamental Principles of Antenna Design

Antennas are the backbone of wireless communication systems, enabling the transmission and reception of electromagnetic waves. Their design is governed by a set of

fundamental principles that determine their performance, efficiency, and suitability for specific applications. These principles include resonance, impedance matching, radiation patterns, polarization, gain, efficiency, and bandwidth. Each of these aspects plays a critical role in ensuring that antennas meet the demands of modern communication technologies, from mobile networks to satellite systems and beyond [1], [15]. In the following sections, we will explore these principles in detail, highlighting their significance and how they influence the design and functionality of antennas [6].

1.3.1. Electromagnetic Theory Basis

Antenna design relies on electromagnetic field theory, which explains how electric and magnetic fields interact and propagate through space. At the foundation of this theoretical framework are Maxwell's equations, which provide a comprehensive and mathematically rigorous description of time-varying electromagnetic phenomena. These equations are not only fundamental to understanding the generation, propagation, and interaction of electromagnetic fields but are also critical for the design, analysis, and optimization of antenna systems. By precisely modeling the relationship between electric and magnetic fields, Maxwell's equations enable the prediction of key antenna performance metrics, such as radiation efficiency, gain, directivity, and bandwidth. Furthermore, they serve as the theoretical basis for cutting-edge techniques like beamforming, MIMO (Multiple Input Multiple Output), and metamaterial-based designs, which are essential for modern wireless communication systems [1], [20].

The differential form of Maxwell's equations is expressed as:

$$\begin{cases} \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \\ \nabla \cdot \mathbf{D} = \rho \\ \nabla \cdot \mathbf{B} = 0 \end{cases} \quad (1.1)$$

Each equation encapsulates a fundamental physical relationship that is indispensable for antenna theory:

- **Faraday's Law** explains the generation of electric fields by time-varying magnetic flux, a mechanism central to wave propagation.

- **Ampère-Maxwell Law** introduces the displacement current term, bridging the gap between static and dynamic fields, crucial for electromagnetic radiation.
- **Gauss's Laws** describe the divergence properties of electric and magnetic fields, ensuring continuity and the absence of magnetic monopoles.

In antenna engineering, these equations form the theoretical scaffold for deriving wave equations that describe the behavior of electromagnetic radiation in free space and guided environments. The vector wave equations for electric and magnetic fields, obtained from Maxwell's equations, are:

$$\begin{cases} \nabla^2 \mathbf{E} - \mu\epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \\ \nabla^2 \mathbf{H} - \mu\epsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \end{cases} \quad (1.2)$$

where μ is the permeability and ϵ the permittivity of the medium. These equations govern the propagation of electromagnetic waves and are the basis for analysing the radiating properties of antennas [2], [21].

1.3.2. Radiation Pattern

The radiation pattern represents the spatial distribution of radiated electromagnetic energy from an antenna. It defines how power varies with direction and is typically described in spherical coordinates [1].

The main components of the radiation pattern are:

- **Main Lobe:** Direction with maximum radiation intensity.
- **Side Lobes:** Radiation in undesired directions, typically minimized in design.
- **Back Lobe:** Radiation opposite to the main lobe direction.
- **Half-Power Beamwidth (HPBW):** The angular range within which the radiated power remains above half of its peak value.
- **First Null Beamwidth (FNBW):** The angular distance between the first nulls on either side of the main lobe [22].

The three main types of radiation patterns commonly discussed in antenna theory are:

1. **Omnidirectional Pattern:** Radiates equally in all directions in a horizontal plane. It provides uniform coverage in all directions and is commonly used in systems where the antenna needs to cover a wide area, like mobile communication base stations (Example: A monopole or dipole antenna) [23].
2. **Directional Pattern:** Focuses the radiation in a specific direction, providing more power in certain directions while minimizing radiation in others. Directional antennas are used for long-range communication or to focus energy in a particular area (Example: Parabolic dish antenna, Yagi-Uda antenna).
3. **Isotropic Pattern:** Theoretical pattern where the antenna radiates equally in all directions in three-dimensional space. It's often used as a reference to compare real antenna patterns (not physically realizable, but a useful model) [24], [22].

1.3.3. Directivity

Directivity is a fundamental parameter in antenna theory that quantifies the concentration of an antenna's radiation in a particular direction. It is defined as the ratio of the radiation intensity in a given direction to the average radiation intensity over all directions. Directivity is a measure of how effectively an antenna focuses energy in a specific direction compared to an isotropic antenna, which radiates energy uniformly in all directions [1], [22].

The directivity D of an antenna in a specific direction (θ, Φ) is given by:

$$D(\theta, \Phi) = \frac{U(\theta, \Phi)}{U_{avg}} \quad (1.3)$$

where:

- $U(\theta, \Phi)$ is the radiation intensity (power per unit solid angle) in the direction (θ, Φ) .
- U_{avg} is the average radiation intensity over all directions, calculated as:

$$U_{avg} = \frac{P_{rad}}{4\pi} \quad (1.4)$$

where P_{rad} is the total power radiated by the antenna.

The **maximum directivity** D_{max} is the directivity in the direction of the antenna's main lobe, where the radiation intensity is highest:

$$D_{max} = \frac{U_{max}}{U_{avg}} \quad (1.5)$$

1.3.4. Antenna Gain

Gain (G) is a fundamental performance parameter in antenna theory, representing the antenna's ability to focus radiated energy in a particular direction relative to an isotropic radiator, which radiates uniformly in all directions. It is a dimensionless quantity often expressed in decibels (dB) and is the product of the antenna's directivity (D) and radiation efficiency (η), expressed as:

$$G = \eta D \quad (1.6)$$

Directivity quantifies the concentration of radiation in a specific direction, while efficiency accounts for losses within the antenna system [1].

High-gain antennas exhibit narrow beamwidths and are essential for applications requiring long-range communication, such as satellite systems, point-to-point wireless links, and radar [22]. Conversely, low-gain antennas, with broader radiation patterns, are suited for applications requiring omnidirectional coverage, such as mobile devices and Wi-Fi routers [5].

Gain is influenced by factors such as antenna geometry, operating frequency, material properties, and design optimization. Advanced techniques, including phased arrays, reflector antennas, and metamaterial-based designs [9], are employed to achieve high gain while minimizing losses and sidelobes. In modern wireless systems, such as 5G and beyond, gain optimization is critical for enhancing signal strength, reducing interference, and improving overall system capacity and reliability [3]. Additionally, gain plays a pivotal role in link budget calculations, ensuring reliable communication over specified distances and under varying environmental conditions [2], [13].

1.3.5. Antenna Impedance and Matching

Antenna impedance plays a critical role in determining the performance and efficiency of an antenna system. It is a complex value, typically consisting of a real component (resistance, R) and an imaginary component (reactance, X), both of which must be carefully managed to ensure that an antenna performs optimally in its intended environment. The real part of the impedance corresponds to the power that is effectively radiated or absorbed by the antenna,

while the imaginary part represents reactive power, which is temporarily stored and then returned to the circuit. Typically, RF systems use standard impedance values such as 50Ω or 75Ω , which have been optimized for most practical applications [1].

However, achieving perfect impedance matching between the antenna, transmission line (e.g., coaxial cables), and the transmitter or receiver is essential for minimizing signal reflections, ensuring the maximum transfer of power, and avoiding losses. When impedance mismatching occurs, part of the transmitted power is reflected back toward the source, resulting in lower system efficiency, increased signal distortion, and potential damage to the transmitter. Additionally, mismatched impedance can lead to the formation of standing waves along the transmission line, further exacerbating power loss and performance degradation. Impedance matching is, therefore, a critical factor in antenna design and must be carefully addressed to maximize the antenna's ability to radiate or receive electromagnetic energy effectively [5].

Several methods can be employed to achieve impedance matching. One of the most common techniques is the use of lumped components, such as inductors and capacitors, to form matching networks. These networks introduce reactive elements that compensate for the mismatched impedance and ensure that the system operates with minimal loss. Transformers are also widely used for impedance matching, as they provide a simple and effective means to match the impedance of the source to that of the antenna. The quarter-wave transformer is another widely used method, involving a section of transmission line with an impedance equal to the geometric mean of the source and load impedances, providing an elegant solution to the problem of impedance mismatch [22]. Stub matching, which involves inserting short-circuited transmission line stubs at specific points along the transmission line, can be used to introduce reactive elements that cancel out mismatched impedance, while tapered transmission lines provide a gradual transition in impedance along the feedline, facilitating a smooth impedance match [16]. Baluns, or balanced-to-unbalanced transformers, are particularly useful when dealing with antennas that exhibit a balanced load, such as dipole antennas, and when interfacing them with unbalanced transmission lines, like coaxial cables. These devices help ensure that the signal is transmitted efficiently between different parts of the system while preventing impedance mismatch [24].

In addition to these passive methods, advanced impedance matching techniques may involve active components or optimization algorithms that take into account the specific properties of the antenna and surrounding environment. Tools such as Smith charts are indispensable for impedance matching [16], providing a graphical method for visualizing the complex relationships between impedance values and aiding in the design of effective matching networks. The application of these tools and methods ensures that antennas are designed to operate at peak efficiency, reducing losses and improving the overall performance of the communication system. Proper impedance matching not only enhances the effective radiation and reception of signals but also plays a pivotal role in reducing interference, increasing the range and reliability of communication systems, and optimizing the use of power in antenna systems [1], [21].

1.3.6. Voltage Standing Wave Ratio (VSWR)

Voltage Standing Wave Ratio (VSWR) is a measure of the impedance matching between a transmission line and its load, such as an antenna. It describes the ratio of the maximum voltage to the minimum voltage along the transmission line, caused by the reflections of the signal due to impedance mismatches. VSWR is an important parameter for assessing the performance of an antenna system, as it provides insight into the level of signal reflection that occurs when the impedance of the load (antenna) does not match the impedance of the transmission line [1], [22].

The VSWR is calculated using the following formula:

$$VSWR = \frac{V_{max}}{V_{min}} \quad (1.7)$$

Where:

- V_{max} is the maximum voltage on the transmission line.
- V_{min} is the minimum voltage on the transmission line.

VSWR is directly related to the reflection coefficient (Γ), which describes the ratio of the reflected signal to the incident signal. The relationship between VSWR and the reflection coefficient is given by:

$$VSWR = \frac{1+|\Gamma|}{1-|\Gamma|} \quad (1.8)$$

Where:

- $|\Gamma|$ is the magnitude of the reflection coefficient, representing the degree of impedance mismatch.

Interpretation of VSWR:

- **VSWR = 1**: This represents perfect impedance matching, where there are no reflections, and all the power is transferred from the source to the load (antenna). It indicates optimal system performance.
- **1 < VSWR < 2**: This range is generally considered acceptable for most communication systems. It means that there is a slight mismatch, but the reflection losses are still relatively low.
- **VSWR = 2**: This indicates a 1:1 power ratio, meaning 25% of the power is reflected. Although this value is still considered usable, it is less efficient.
- **VSWR > 2**: Higher values indicate poor impedance matching, resulting in higher levels of reflected power and inefficient operation. VSWR values above 3 are often considered problematic and may require corrective measures like impedance matching.

Impact of VSWR on Performance:

- **High VSWR**: A high VSWR value means a significant portion of the signal is reflected back toward the transmitter, leading to power loss, potential damage to the transmitter, and decreased efficiency of the antenna. It can also cause standing waves along the transmission line.
- **Low VSWR**: A low VSWR indicates that the system is well-matched, with minimal reflection. This results in efficient signal transfer, better radiation performance, and less risk of damage to the system components [2], [6].

1.3.7. Antenna Polarization

Refers to the orientation of the electric field vector of an electromagnetic wave radiated by an antenna. The three main types of polarization are:

1. **Linear Polarization:** The electric field vector oscillates in a single plane along the direction of wave propagation. Linear polarization can be further divided into:

- **Vertical Polarization:** The electric field is perpendicular to the Earth's surface.
- **Horizontal Polarization:** The electric field is parallel to the Earth's surface.

Linear polarization is widely used in ground-based communication systems like mobile networks and broadcast television [22].

2. **Circular Polarization:** The electric field vector rotates in a circular motion as the wave propagates. It can be classified as:

- **Right-Hand Circular Polarization (RHCP):** The electric field rotates clockwise when viewed along the direction of propagation.
 - **Left-Hand Circular Polarization (LHCP):** The electric field rotates counterclockwise when viewed along the direction of propagation.
- Circular polarization is beneficial in satellite communication and radar, as it is less sensitive to the orientation of the receiving antenna.

3. **Elliptical Polarization:** A more general form where the electric field vector describes an ellipse. It occurs when the horizontal and vertical components have unequal amplitudes or a phase difference other than 90 degrees. Depending on the direction of rotation, elliptical polarization can also be right-handed or left-handed [1].

Choosing the correct type of polarization is essential for efficient communication, as mismatched polarization between transmitting and receiving antennas results in polarization loss and reduced signal strength [24], [6].

1.3.8. Bandwidth and Q-Factor

1.3.8.1. *Bandwidth*

refers to the range of frequencies over which an antenna or system operates effectively. It is typically defined by the frequencies where performance metrics (such as return loss, gain, or efficiency) remain within acceptable limits. Bandwidth is often expressed as a percentage of the center or resonant frequency:

$$\text{Bandwidth} = \frac{f_{upper} - f_{lower}}{f_{center}} \times 100 \quad (1.9)$$

Where:

- f_{upper} and f_{lower} are the upper and lower cutoff frequencies,
- f_{center} is the center frequency [6].

1.3.8.2. Q-Factor (Quality Factor)

Q-Factor is a dimensionless parameter that quantifies the sharpness of resonance in a resonant system. It is defined as the ratio of stored energy to dissipated energy per cycle:

$$Q = \frac{2\pi \times \text{stored energy}}{\text{energy dissipated per cycle}} \quad (1.10)$$

Alternatively, in terms of bandwidth:

$$Q = \frac{f_{center}}{\text{Bandwidth}} \quad (1.11)$$

A high Q-factor indicates a narrow bandwidth and strong resonance, while a low Q-factor represents a broad bandwidth and weaker resonance [22].

1.3.9. Mutual Coupling and Scattering Effects

In complex systems, interactions between closely placed antenna elements cause mutual coupling, affecting performance. Scattering parameters (S-parameters) characterize these effects.

1.3.9.1. Mutual Coupling Analysis

Mutual coupling refers to the interaction between antennas when placed in proximity to each other. It occurs when electromagnetic fields from one antenna induce currents or voltages in nearby antennas. This coupling modifies the input impedance, alters the radiation patterns, and can lead to performance degradation in multi-antenna systems such as multiple-input multiple-output (MIMO) systems, beamforming arrays, and phased arrays. The mutual impedance Z_{ij} between antennas i and j is a complex quantity that defines the coupling:

$$Z_{ij} = \frac{V_i}{I_j} \quad (1.12)$$

where:

- V_i is the induced voltage at antenna i due to current I_j in antenna j [1].

Mutual Coupling Mechanisms:

1. **Near-Field Coupling:** Dominated by reactive fields (electric and magnetic), it is significant when antennas are spaced at less than half a wavelength.
2. **Far-Field Coupling:** Influenced by radiated fields, it occurs at greater separations but still affects beamforming accuracy and sidelobe levels [5].

1.3.9.2. Scattering Effects and Their Influence

Scattering effects in antenna systems arise from interactions between electromagnetic waves and nearby objects or array elements. This interaction leads to redirection, phase shifts, and energy distribution changes, impacting both near-field and far-field behaviors.

Types of Advanced Scattering:

1. **Mutual Scattering in Arrays:** The presence of multiple elements creates a complex interaction of radiating and scattered fields, modifying array factor calculations and beam shape.
2. **Surface and Edge Diffraction:** Scattering from structural edges introduces secondary waves that combine with the primary wave, altering the radiation pattern [4].

Advanced Scattering Parameters:

- **Radar Cross Section (RCS):** Quantifies how much power is scattered in a given direction relative to the incident power.
- **Normalized Scattering Matrix:** Used for multi-element systems, incorporating coupling and phase shifts into system-level analysis.

Computational and Theoretical Models

- **Full-Wave Electromagnetic Simulations:** Finite-Difference Time-Domain (FDTD), Method of Moments (MoM), and Finite Element Method (FEM) allow precise modeling of mutual coupling and scattering in complex environments.
- **Integral Equation Methods:** Solving Green's functions for mutual interactions provides analytical insights into far-field coupling.

Impact on Performance

1. **Pattern Distortion and Gain Reduction:** Coupling and scattering redistribute radiated power, impacting main lobe direction and efficiency.
2. **Reduced Beamforming Accuracy:** Phase variations due to scattering degrade array steering performance.
3. **Noise and Interference Enhancement:** Undesirable coupling amplifies interference in sensitive systems [6], [24].

1.3.10. Near and Far Field

The electromagnetic fields around an antenna are typically divided into two primary regions: the near field and the far field. These regions are defined based on the distance from the antenna and the behavior of the electromagnetic fields. Understanding the distinction between these regions is crucial for analyzing antenna performance, designing measurement setups, and optimizing communication systems.

1.3.10.1. Near Field

The near field is the region closest to the antenna, where the electromagnetic fields are still forming and have not fully transitioned into radiating waves. This region is characterized by complex field structures and is further divided into two sub-regions:

$$R < 0.62 \sqrt{\frac{D^3}{\lambda}} \quad (1.13)$$

where D is the largest dimension of the antenna and λ is the wavelength [1].

- **Characteristics:** Dominated by reactive fields (electric and magnetic fields that store energy rather than radiate it). These fields decay rapidly with distance and do not contribute to far-field radiation.
- **Applications:** Important for applications like wireless power transfer, inductive coupling, and near-field communication (NFC).
- **Radiating Near Field (Fresnel Region):**
 - **Distance:** Extends from the reactive near field to approximately

$$R < \frac{2D^2}{\lambda} \quad (1.14)$$

- **Characteristics:** Contains both reactive and radiating fields. The field structure is complex, with significant variations in amplitude and phase.
- **Applications:** Used in near-field measurements and antenna diagnostics [22].

1.3.10.2. *Far Field*

The far field is the region beyond the near field, where the electromagnetic fields have fully transitioned into radiating waves. This region is characterized by predictable and simplified field behavior:

- **Distance:** Begins at approximately

$$R \geq \frac{2D^2}{\lambda} \quad (1.15)$$

and extends to infinity.

- **Characteristics:**
 - The fields propagate as **plane waves**, with the electric and magnetic fields perpendicular to each other and to the direction of propagation.
 - The field strength decays as $\frac{1}{R}$, where **R** is the distance from the antenna.
 - The radiation pattern is stable and independent of distance, making it ideal for performance evaluation.
- **Applications:** Far-field measurements are used to characterize antenna performance, including gain, directivity, and radiation patterns [1], [2].

1.4. Antenna Type

Antennas are classified into various types based on their design, operating principles, and performance characteristics. Each type offers distinct advantages and limitations, making it suitable for specific applications and performance criteria. Below is a detailed overview of

major antenna types, focusing on their design principles, operational characteristics, advantages, limitations, and applications.

1.4.1. Wire Antennas

Wire antennas are among the simplest and most widely used types of antennas. They are typically composed of straight or curved conductive elements and are characterized by their ease of design and fabrication [1].

1.4.1.1. Dipole Antennas

A dipole antenna (DA) consists of two conductive elements, such as rods or wires, aligned end-to-end and typically fed at the center by a transmission line. When an alternating current is applied, the dipole radiates electromagnetic waves, and the radiation pattern is determined by the current distribution along the elements. The length of the dipole is usually designed to be half the wavelength of the operating frequency, which is why it is often referred to as a "half-wave dipole." This design ensures efficient radiation and reception of signals. The radiation pattern of a dipole is typically omnidirectional in the plane perpendicular to the antenna's axis, making it widely used in applications like radio broadcasting, television, and wireless communication systems. The simplicity and effectiveness of dipole antennas make them a fundamental and widely utilized type of antenna in the field of telecommunications [2], [22].

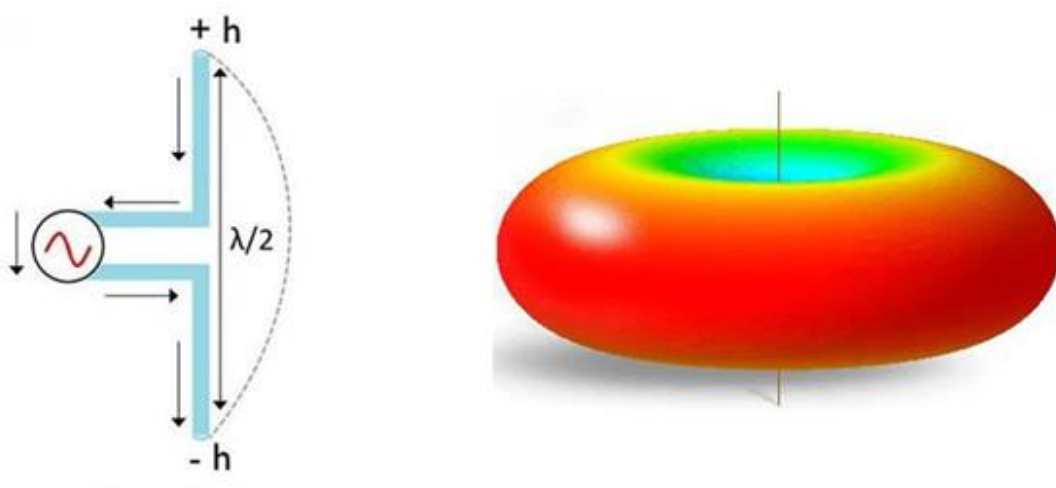


Figure 1.1. half-wave dipole Antenna and Its 3D radiation pattern

1.4.1.2. *Dipole Antennas*

A monopole antenna is a type of radio antenna that consists of a single conductive element, such as a rod or wire, mounted perpendicularly over a conductive ground plane. It operates as half of a dipole antenna, with the ground plane acting as a virtual mirror to simulate the missing half, effectively creating an image of the monopole. This design allows the monopole to radiate electromagnetic waves efficiently when an alternating current is applied. The radiation pattern of a monopole antenna is typically omnidirectional in the horizontal plane (parallel to the ground plane), making it ideal for applications where uniform coverage is required, such as in FM radio broadcasting, mobile communication devices, and vehicle-mounted systems [10].

The length of the monopole element is often a quarter of the wavelength of the operating frequency, which is why it is commonly referred to as a "quarter-wave monopole." This length ensures optimal impedance matching and radiation efficiency. The performance of a monopole antenna is highly dependent on the size and conductivity of the ground plane, as a poor or insufficient ground plane can lead to reduced radiation efficiency and distorted radiation patterns. Monopole antennas are widely favored for their simplicity, compact size, and ease of installation, making them a popular choice in both commercial and consumer wireless communication systems [1], [21].

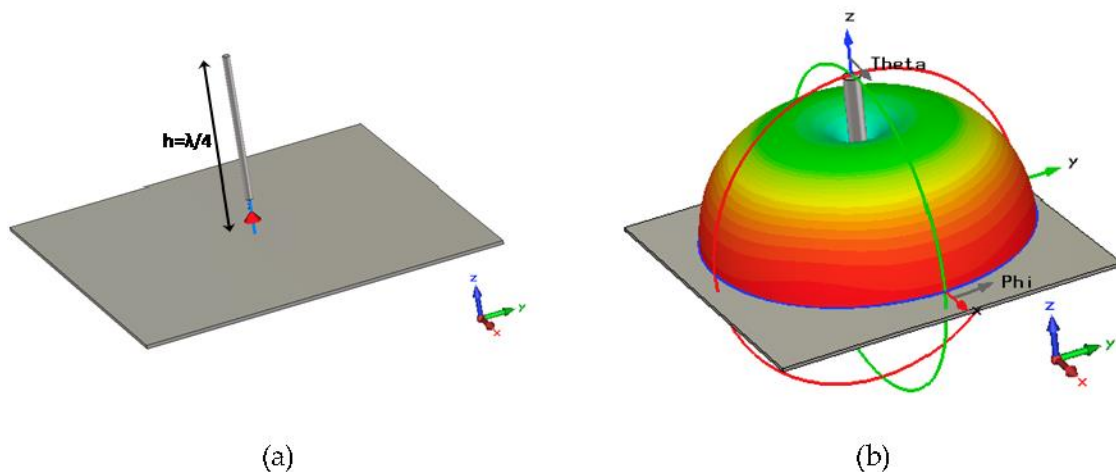


Figure 1.2. (a) Monopole antenna (b) and its 3D radiation pattern

1.4.1.3. *Loop Antennas*

A loop antenna, characterized by its closed-loop structure of conductive material, is a versatile and efficient antenna type widely utilized in both transmitting and receiving applications. It is broadly classified into small loop antennas, with a circumference much smaller than the operating wavelength, and large loop antennas, with a circumference comparable to or greater than the wavelength. Small loops are predominantly used in receiving applications due to their high sensitivity to magnetic fields, excellent noise rejection capabilities, and compact design, making them ideal for AM radio, direction-finding, and RFID systems. In contrast, large loops, which operate as resonant antennas, are efficient radiators suitable for transmitting applications, such as amateur radio and shortwave communication. The radiation patterns of loop antennas vary based on their size and design, with small loops exhibiting bidirectional patterns and large loops often displaying omnidirectional or directional characteristics. Their adaptability, noise immunity, and ability to be tuned for specific frequencies make loop antennas a critical component in modern wireless communication systems, offering significant potential for innovation in antenna design and optimization for emerging technologies [1], [6].



Figure 1.3. HF/VHF/UHF Horizontal Omni Loop Antenna

1.4.2. Aperture Antennas

Aperture antennas are a class of antennas that radiate or receive electromagnetic waves through an opening, or aperture, rather than through conductive elements like wires or rods. They are known for their ability to focus electromagnetic energy into a directed beam, offering high gain and directivity. Common types include horn antennas, parabolic reflectors, slot antennas, and lens antennas, each with unique characteristics suited for specific applications. Aperture antennas are widely used in radar systems, satellite communication, radio astronomy, and high-frequency wireless communication due to their efficiency and precision in beam control [1], [25].

1.4.2.1. Horn Antennas

Horn antennas are a type of aperture antenna that use a flared waveguide to direct electromagnetic waves into a focused beam. They are characterized by their simple structure, high gain, and wide bandwidth, making them highly efficient for high-frequency applications. The flared shape of the horn helps to match the impedance between the waveguide and free space, reducing signal reflection and improving radiation efficiency. Horn antennas are commonly used in microwave and millimeter-wave systems, such as radar, satellite communication, and radio astronomy, where precise beam control and high directivity are required. They are also used as feed elements for larger reflector antennas. Due to their robustness, ease of construction, and reliable performance, horn antennas are a fundamental component in many wireless communication and sensing systems [25], [26].

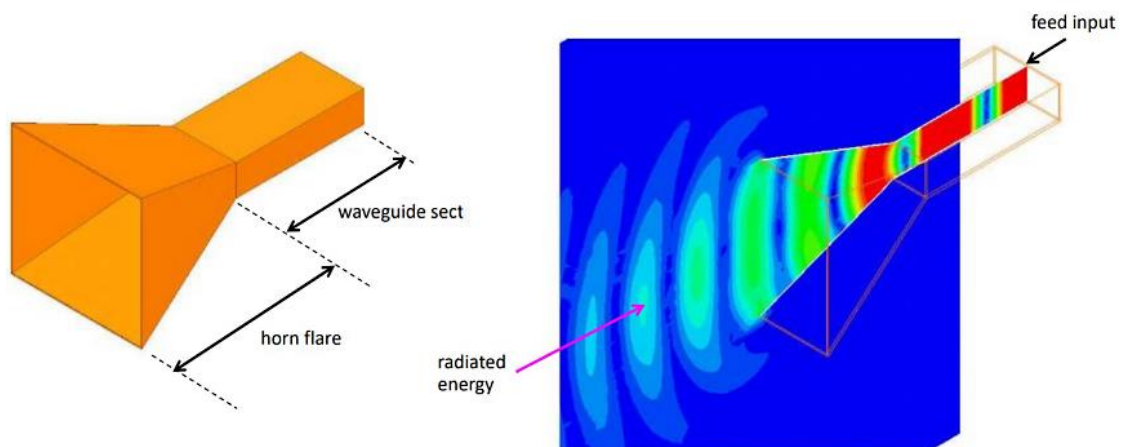


Figure 1.4. Example of Horn Antenna and its radiated energy

1.4.2.2. Parabolic Reflector Antennas

A parabolic reflector antenna is a high-gain antenna that uses a parabolic-shaped reflecting surface to focus electromagnetic waves into a narrow, directional beam. The parabolic shape ensures that incoming waves parallel to the antenna's axis are reflected to a single focal point, where the feed antenna (such as a horn or dipole) is placed. This design provides exceptional directivity and gain, making it ideal for long-distance communication, satellite links, radio astronomy, and radar systems. Parabolic reflector antennas are widely used in applications requiring precise beam control and high signal strength, such as deep-space communication, television broadcasting, and wireless backhaul networks. Their ability to achieve high efficiency and focus energy over long distances makes them a cornerstone of modern wireless and satellite technology [22], [25].

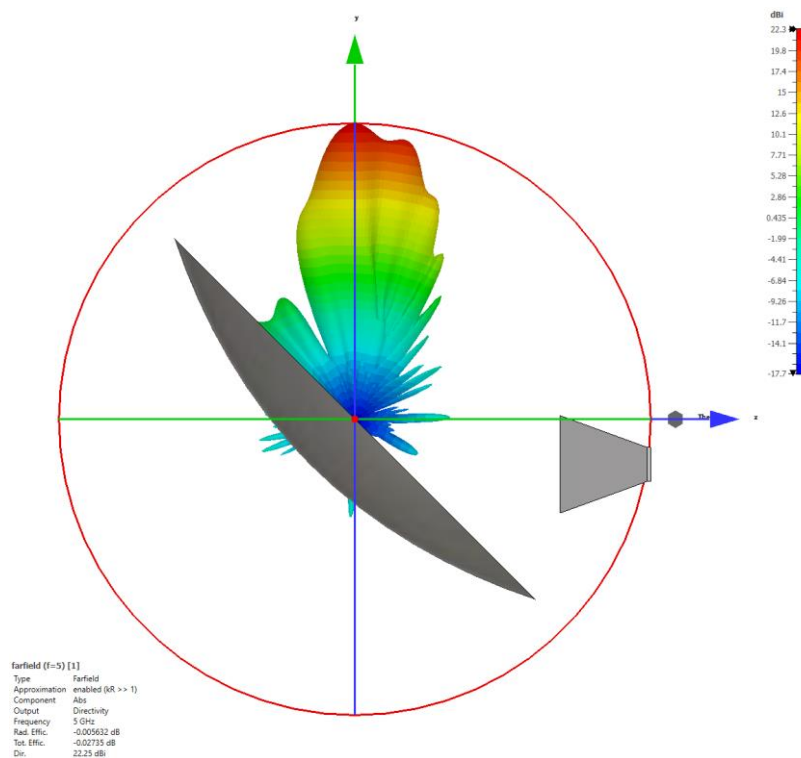


Figure 1.5. Parabolic reflector Antenna with its 3D radiation pattern

1.4.3. Microstrip Antennas

Microstrip antennas, also known as patch antennas, are planar antennas widely used in wireless communication, radar, and satellite systems. Their lightweight, low profile, and ease of fabrication make them ideal for applications requiring compact and conformal designs. A typical microstrip antenna consists of a radiating metallic patch on one side of a dielectric substrate with a ground plane on the other.

1.4.3.1. Patch Antennas

A patch antenna is a type of microstrip antenna consisting of a flat metallic patch mounted on a dielectric substrate with a ground plane underneath. It radiates electromagnetic waves from the edges of the patch. Although patch antennas are known for their compact size, lightweight design, and ease of fabrication, making them suitable for applications like wireless communication, satellite systems, and automotive radar. Despite their narrow bandwidth and low gain, performance can be enhanced using arrays, stacked patches, or advanced feeding techniques. They are widely used due to their simplicity and compatibility with printed circuit board (PCB) manufacturing [6], [10].

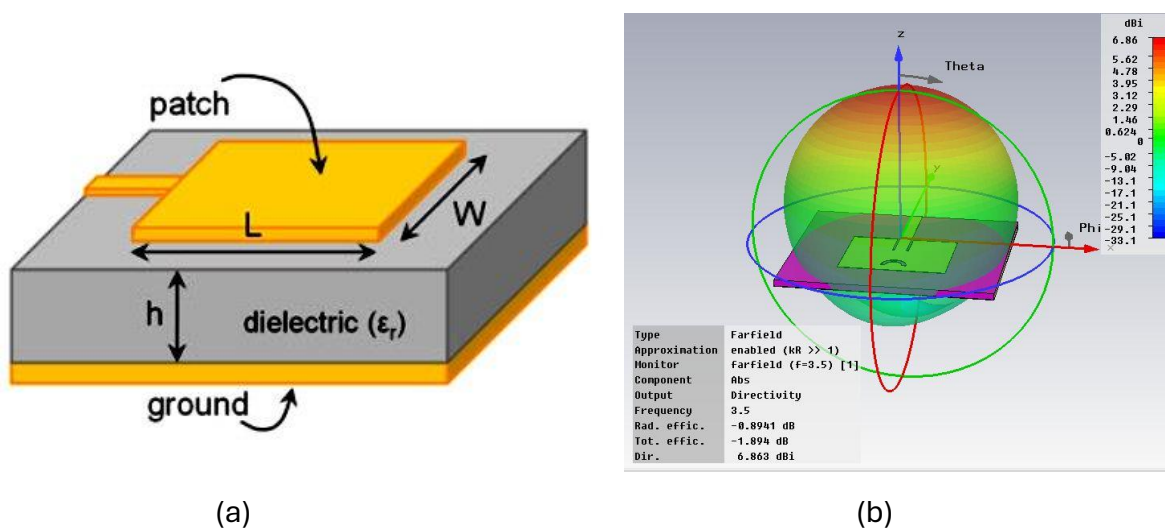


Figure 1.6. (a) Patch antenna, (b) its 3D radiation pattern

1.4.3.2. Printed Dipole Antennas

A printed dipole antenna (PDA) is a flat, planar version of a traditional dipole antenna, made by etching two symmetrical metal strips onto a dielectric substrate. It is compact, lightweight, and easy to integrate with other circuits using PCB technology. This antenna radiates in a bidirectional pattern, with strong signals perpendicular to the plane of the dipole. Printed dipole antennas are valued for their simplicity and cost-effectiveness, making them ideal for applications in wireless communication, RFID systems, and portable devices. Advanced designs improve their performance by adding reflectors, directors, or combining dipoles in arrays to enhance gain, bandwidth, and directivity. These antennas are crucial in modern systems due to their flexibility in design and ease of mass production [10], [27].

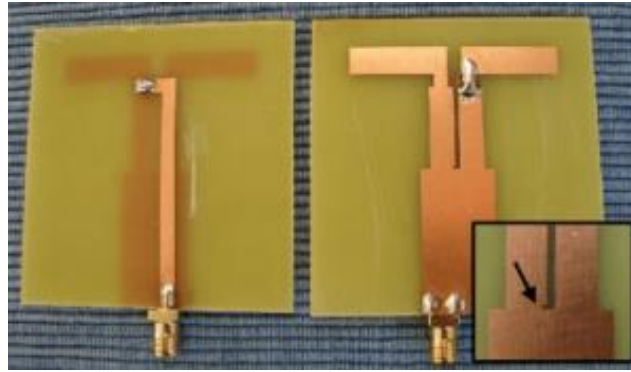


Figure 1.7. Printed dipole antenna side views

1.4.4. Array Antennas

An array antenna is a smart network of individual antenna elements that work together to achieve high performance. Each antenna in the array can be controlled independently, allowing the system to direct its energy with pinpoint accuracy. By adjusting the phase and amplitude of signals sent to each element, array antennas can shape, steer, and focus the beam in any direction, without needing to physically move the antenna.

This ability to adapt in real-time makes array antennas incredibly versatile. They are essential in cutting-edge applications like 5G communication, radar systems, satellite technologies, and military defense. Whether you're sending data over vast distances, tracking objects with high precision, or connecting millions of users simultaneously, array antennas deliver unparalleled performance. They can increase signal strength, reduce interference, and improve coverage, making them indispensable in today's high-tech world [16], [17].



Figure 1.8. Examples of rectangular, circular, and hexagonal antenna arrays.

1.4.5. Emerging Antenna Technologies

Emerging antenna technologies represent a paradigm shift in the design and functionality of modern communication systems, integrating sophisticated approaches to meet the growing

demands of high-speed, high-capacity, and flexible networks. Advanced concepts such as Massive MIMO leverage dense antenna arrays to enable spatial multiplexing and beamforming, significantly enhancing signal strength, capacity, and network efficiency. Metamaterial-based antennas introduce engineered structures capable of controlling electromagnetic waves with subwavelength precision, facilitating miniaturization and unprecedented performance across diverse frequency bands, including terahertz. Reconfigurable antenna systems, utilizing adaptive techniques like software-defined radio (SDR), offer dynamic control over radiation patterns, polarization, and frequency, optimizing the performance in response to varying environmental conditions and user demands. Phased arrays enable electronic beam steering, supporting applications in 5G and beyond by facilitating real-time communication with minimal latency. Furthermore, the integration of artificial intelligence (AI) and machine learning (ML) into antenna design and beamforming algorithms promises autonomous optimization [28], ensuring efficient spectrum management and enhanced network reliability in heterogeneous environments. These technological advancements, essential for the deployment of next-generation wireless networks, are poised to enable innovations in terahertz communication, quantum networks, IoT ecosystems, and autonomous systems, all of which will require the seamless integration of these intelligent, high-performance antenna systems [9], [16].

1.4.5.1. *Reconfigurable Antennas*

Reconfigurable antennas represent a significant advancement in antenna design, enabling a high degree of adaptability and flexibility in wireless communication systems. These antennas utilize cutting-edge technologies such as PIN diodes, microelectromechanical system (MEMS), and software-defined radio (SDR) to allow real-time modification of key parameters like frequency, polarization, and radiation pattern. This dynamic reconfiguration capability makes them essential for multi-band operations, efficient beamforming, and polarization control, which are critical for applications in 5G, 6G, satellite communications, and autonomous systems. The ability to adjust to different environmental conditions or user needs without physically altering the antenna provides a substantial advantage in spectrum efficiency, signal quality, and network performance. Furthermore, by reducing the need for multiple fixed antennas, reconfigurable designs enable more compact, cost-effective systems, which are particularly beneficial in IoT devices, mobile platforms, and drones. When integrated with cognitive radio networks and enhanced by AI-driven algorithms, these

antennas offer real-time optimization, ensuring seamless communication even in highly dynamic and congested networks. As the demand for scalable, high-performance networks grows, reconfigurable antennas will play a pivotal role in shaping the future of next-generation communication systems, enabling smarter, more efficient, and adaptable wireless infrastructures [29], [30].

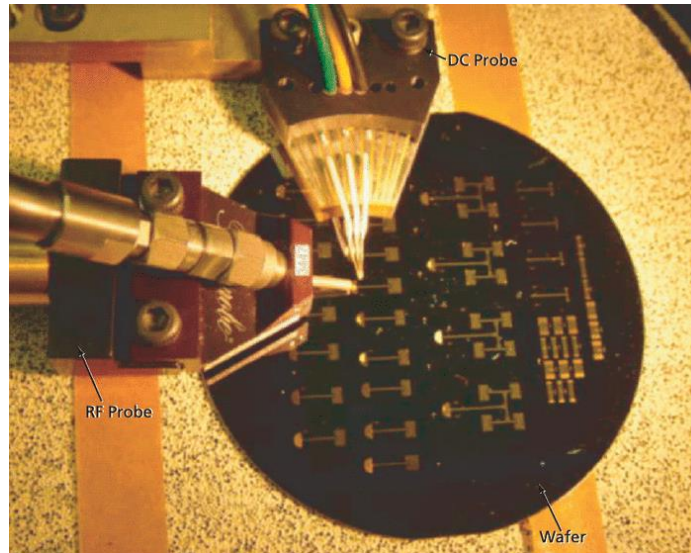


Figure 1.9. Reconfigurable Patch Antenna

1.4.5.2. Metamaterial Antennas

represent an exciting frontier in antenna design, offering unprecedented capabilities by harnessing the unique electromagnetic properties of engineered materials. Unlike traditional antennas, which are limited by the natural characteristics of the materials they are made from, metamaterial antennas can manipulate electromagnetic waves in novel ways. This ability allows for compact, high-performance antennas that can achieve higher gain, broader bandwidths, and enhanced efficiency—all while being significantly smaller in size. With features like dynamic frequency adjustment, precise polarization control, and advanced beam shaping, these antennas are ideal for cutting-edge applications in 5G, 6G [13], satellite communications, and terahertz systems. As the demand for faster, more reliable communication grows, metamaterial antennas are pushing the boundaries of what's possible in wireless technology, enabling smarter, more efficient systems that can meet the challenges of tomorrow's connected world [9], [16].

1.4.5.3. Plasmonic Antennas

Type of antenna that uses the unique properties of plasmonics, which involves the interaction between light and electrons on metal surfaces. These antennas work by exciting surface plasmons, which are oscillations of electrons at the interface between a metal and a dielectric material, allowing them to focus and manipulate electromagnetic waves at very small scales. Unlike traditional antennas, plasmonic antennas can be much smaller than the wavelength of the electromagnetic waves they transmit or receive, making them ideal for applications in nanotechnology, biosensing, and optical communications. They offer enhanced energy concentration, enabling efficient transfer of electromagnetic energy at the nanoscale, and can operate in the infrared and visible light spectrum. The small size, high sensitivity, and ability to manipulate light with precision make plasmonic antennas particularly useful in biosensors [31], chemical detection, and nano-imaging, where high sensitivity and precise control of light are crucial [32].

1.5. Physical phenomena in Antenna Design

Antenna design is inherently governed by various physical phenomena that influence how electromagnetic waves are transmitted, received, and propagated. Understanding these phenomena is crucial for optimizing antenna performance and ensuring that the antenna meets the desired specifications for a given application. The key physical phenomena involved in antenna design include:

1.5.1. Electromagnetic Radiation

Antennas operate by converting electrical energy into electromagnetic radiation and vice versa. This process is explained by Maxwell's equations, which describe how time-varying electric and magnetic fields interact. The shape, size, and structure of an antenna determine its ability to radiate energy effectively [33]. Dipole and monopole antennas are classic examples where the length of the antenna is typically a fraction of the wavelength of the transmitted signal, ensuring efficient radiation [20], [6].

1.5.2. Resonance

Antennas are designed to operate at specific resonant frequencies where they achieve maximum efficiency. Resonance occurs when the physical dimensions of the antenna

correspond to a multiple or fraction of the wavelength of the operating frequency. This phenomenon ensures minimal reactive power and maximum radiated power [1], [20].

1.5.3. Diffraction

Diffraction refers to the bending of electromagnetic waves around obstacles or edges when the waves encounter a barrier or sharp change in surface. It allows waves to propagate beyond obstructions and reach areas not in the direct line of sight of the transmitting antenna. The amount of diffraction depends on the wavelength relative to the size of the obstacle. Lower-frequency waves (longer wavelengths) diffract more effectively than higher-frequency waves, which are more prone to shadowing effects [33]. In antenna systems, diffraction is particularly relevant for:

- Urban environments where buildings and structures block direct paths.
- Low-frequency antennas where signal bending improves coverage around obstacles [24].

1.5.4. Reflection

Reflection occurs when electromagnetic waves encounter a surface or boundary and are partially or wholly redirected back into the medium from which they originated. The amount of reflection depends on the material properties, such as conductivity and permittivity, and the angle of incidence [33]. Reflection is a key factor in:

- Designing antenna arrays where phased elements leverage reflections to enhance directivity [16].
- Understanding multipath propagation, where multiple reflections cause signal fading or interference.
- Optimizing reflector antennas (e.g., parabolic dishes), where surfaces focus energy in a specific direction to increase gain.

Reflection can enhance or degrade system performance depending on how well it is controlled. In some systems, reflected signals combine constructively with direct signals, while in others, they cause destructive interference [22].

1.5.5. Refraction

Refraction is the bending of electromagnetic waves when they pass from one medium to another with a different refractive index. The change in wave speed alters the direction of propagation, governed by Snell's Law. This phenomenon is significant in:

- Designing dielectric lenses or radomes that shape or protect radiated signals.
- Evaluating atmospheric effects on long-distance communication, particularly in satellite and terrestrial microwave links, where varying air density layers can bend signals and impact coverage.

Understanding these phenomena is crucial for designing antennas and systems that operate efficiently in complex real-world environments. By accounting for diffraction, reflection, and refraction, engineers can optimize coverage, reduce interference, and improve overall system reliability in wireless communications [6], [33].

1.5.6. Skin Effect in Antenna design

The skin effect is a physical phenomenon that affects the behavior of alternating current (AC) in conductors, particularly at higher frequencies. It describes how AC tends to flow near the surface of a conductor rather than uniformly throughout its cross-section. This effect has significant implications for the design and efficiency of antennas and transmission lines operating at radio and microwave frequencies [10].

When AC current flows through a conductor, the changing magnetic field induces eddy currents within the material. These induced currents oppose the flow of current in the central region of the conductor, causing the majority of the current to be confined to a thin layer near the surface. The depth at which the current density falls to about 37% of its value at the surface is known as the skin depth (δ) and is given by:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} \quad (1.16)$$

Where:

- ρ is the resistivity of the material (ohm-meter),
- $\omega = 2\pi f$ is the angular frequency of the current (radians per second),
- μ is the permeability of the material (henries per meter),

- f is the frequency (hertz).

As frequency increases, the skin depth decreases, confining the current to an increasingly thinner layer of the conductor [33].

1.5.7. Multipath Propagation

Multipath propagation refers to the phenomenon where electromagnetic waves transmitted from an antenna take multiple paths to reach the receiving antenna. These paths may involve reflection, diffraction, and scattering due to obstacles such as buildings, trees, and other structures in the environment [24]. This phenomenon significantly impacts the performance of wireless communication systems and must be carefully considered in antenna design [1].

1.5.8. Attenuations

Attenuation refers to the gradual reduction in the strength or power of a signal as it propagates through a medium. It is a critical factor in antenna design and wireless communication systems, influencing the range, reliability, and quality of transmitted signals. Understanding and managing attenuation is essential for optimizing communication performance [20].

1.6. Principle of Composite Antennas

Composite antennas refer to antennas that combine the features and characteristics of two or more different types of antenna designs. The goal of using composite antennas is to harness the benefits of each individual type to achieve superior performance characteristics such as high gain, wide bandwidth, efficient beamforming, or miniaturization. These antennas are commonly used in complex communication systems, radar applications, and in technologies requiring specific design optimizations, such as in the field of embedded systems or millimetre-wave radar [15].

The theoretical foundation of composite antennas lies in combining different types of radiating elements (such as dipoles, horns, or dielectric materials) to take advantage of the distinct benefits each brings. By combining these elements, composite antennas are designed to overcome limitations that might exist if the elements were used individually [17].

Some key principles include:

1.6.1. Combination of Geometry

Composite antennas often use a combination of different geometries, such as combining elements like microstrip patches with dielectric resonators or horn shapes with planar radiators. This combination helps tailor the antenna to specific needs such as size reduction, increased bandwidth, or higher gain [16].

1.6.2. Dual Functionality

A composite antenna might perform more than one function simultaneously. For example, one part of the antenna may be optimized for transmitting high-frequency signals while another part may be optimized for receiving low-frequency signals. This is particularly useful in multi-function radar systems or communication arrays.

1.6.3. Size and Weight Reduction

One of the driving factors for developing composite antennas is the need for size reduction without compromising performance. By incorporating different materials (e.g., dielectric materials or microstrip designs), the size of the antenna can be reduced while still achieving high radiation efficiency and directional properties [33].

1.7. Conclusion

Antennas are indispensable components in wireless communication systems, bridging the gap between electronic circuits and the electromagnetic spectrum. Their ability to transmit and receive electromagnetic waves underpins a vast array of modern technologies, from mobile networks and satellite communications to radar systems and the rapidly expanding Internet of Things (IoT). The performance and effectiveness of an antenna are defined by critical parameters, including input impedance, reflection coefficient, gain, directivity, bandwidth, and radiation efficiency, all of which influence signal quality, reliability, and energy efficiency.

The state of the art in antenna technology reflects a continuous push toward innovation to meet the ever-increasing demands for higher data rates, broader bandwidth, lower latency, and better connectivity. Advanced designs such as beamforming antennas for focused signal transmission, massive MIMO systems for enhanced capacity, and reconfigurable antennas that adapt to changing conditions are now at the forefront of research. Additionally, the

exploration of millimeter-wave frequencies and the integration of metamaterials and dielectric lenses are transforming antenna performance to support emerging applications like 5G, 6G, autonomous vehicles, augmented reality, and smart cities.

Future advancements will focus on creating highly efficient, compact, and multifunctional antennas capable of operating across wide frequency ranges and harsh environments while minimizing energy consumption. Antenna technology, therefore, remains a cornerstone of communication innovation, playing a vital role in shaping the connectivity of tomorrow. As the field evolves, the combination of novel materials, cutting-edge design methodologies, and powerful simulation tools will be key to overcoming new challenges and unlocking the full potential of next-generation wireless networks.

Chapter 2. Horn Antennas Modeling and Design

2.1. Introduction

The smooth-wall conical horn antenna (SWCHA) is a key component in microwave systems, widely utilized for its simplicity, reliability, and adaptability. Its cylindrical geometry, featuring rotational symmetry, makes it especially suitable for a variety of polarization modes, including linear and circular polarizations. For circular polarization, smooth-wall horns often employ two orthogonal coaxial-to-waveguide transducers, driven in phase quadrature. This configuration is particularly valuable in satellite communication, radio astronomy, and radar systems, where robust and precise polarization control is essential [1-3].

The mechanical advantages of SWCHA include ease of manufacturing and lighter weight compared to alternative designs. This simplicity allows them to be cost-effective while maintaining a high level of performance for general-purpose applications. However, these antennas exhibit certain performance challenges that limit their effectiveness in high-precision scenarios [1-4].

2.2. Physical description

A horn antenna typically consists of two primary components: a circular waveguide section and a smooth profiled flare section. Together, these components create a structure optimized for efficiently transitioning electromagnetic waves from the confined environment of a waveguide to free-space radiation. The design and geometric features of these sections are critical to the antenna's performance, as they influence its impedance matching, beam characteristics, and radiation efficiency [6].

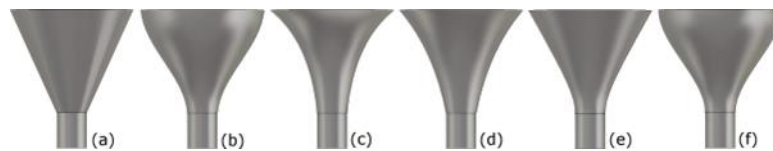


Figure 2.1. A comparison of the various profiles: (a) linear, (b) sinusoidal ($p=2$, $A=0.8$), (c) tangential ($p=2$, $A = 0.8$), (d) exponential, (e) hyperbolic and (f) polynomial ($p=2$).

2.2.1. Circular Waveguide Section

The circular waveguide serves as the input region of the horn, where electromagnetic waves are guided in a well-defined mode, typically the fundamental TE_{11} mode. This section

ensures the wave's polarization and mode purity before entering the flare. The circular cross-section also provides rotational symmetry, making the horn compatible with a wide range of polarization states, including linear and circular polarizations [3].

- **Role in Transition:** The waveguide's dimensions (diameter and length) are designed to maintain mode purity and facilitate a smooth transition to the flared section.
- **Material Considerations:** Materials are typically chosen for their low-loss properties at microwave and millimeter-wave frequencies, ensuring minimal energy dissipation.

2.2.2. Smooth Profiled Flare section

The profiled flare section is the defining feature of the horn antenna, where the wave transitions from the confined waveguide to free space. The flare is designed to gradually match the waveguide's impedance with that of free space, reducing reflections and improving radiation efficiency.

Numerous enhancement techniques have been developed to optimize SWCHA while retaining their simplicity and cost-effectiveness compared to corrugated horns [7].

2.3. Conclusion Technique for Improving SWCHA

2.3.1. Profiling the Flare

One of the most effective approaches to enhancing the performance of smooth-wall horns is profiling the flare, where the geometry of the horn's expanding section is tailored to optimize specific radiation characteristics. Profiles such as sinusoidal, tangential, exponential, hyperbolic, and polynomial are commonly employed. Each profile has unique attributes, allowing for customization to meet the needs of particular applications [7], [25].

2.3.2. Advantages of profiling

2.3.2.1. *Ease of Manufacturing*

At millimeter-wave frequencies, where precise fabrication is crucial, smooth-wall horns are easier and less expensive to produce compared to corrugated horns. This makes them particularly advantageous for high-frequency applications, where the intricate designs of corrugations become cost-prohibitive and technically challenging to fabricate [22].

2.3.2.2. *Mode Conversion Control*

Profiling helps control mode conversion within the waveguide, reducing unwanted higher-order modes and improving the purity of the dominant mode (TE₁₁).

2.3.2.3. *Symmetry and radiation Pattern Improvements*

Carefully designed profiles enhance the symmetry of the radiation pattern, reduce sidelobe levels, and mitigate diffraction-induced distortions. This makes profiled smooth-wall horns suitable for applications requiring precise radiation characteristics, such as satellite communication and radar [15].

2.3.3. Limitation of profiling

Despite its advantages, profiling has notable drawbacks compared to corrugated designs:

2.3.3.1. *Limited Cross-Polarization suppression*

Profiled smooth-wall horns struggle to achieve the same level of low cross-polarization performance over a broad frequency band as corrugated horns. This limitation restricts their utility in applications demanding strict polarization purity, such as some radio astronomy or high-precision radar systems [34].

2.3.3.2. *Complex design considerations*

While profiles may be implemented in isolation, combining multiple profiles can lead to intricate structures that require advanced modeling and optimization. This complexity, while offering performance benefits, may increase design and analysis time [35].

2.4. Feed Methods for Horn Antennas

2.4.1. Coaxial Probe Feed

In a coaxial probe feed system, the center conductor of a coaxial cable extends into the waveguide or horn aperture, exciting the electromagnetic field. This method is typically used for antennas requiring linear polarization.

- **Advantages:**
 - Simple and cost-effective.

- Directly excites the dominant mode (e.g., TE_{11} or TE_{10}) in the waveguide.

- **Limitations:**

- May introduce asymmetry in the field distribution due to localized excitation.
- Best suited for small-scale or lower-frequency systems [36].

2.4.2. Waveguide Feed

The waveguide feed is a robust and widely used technique, particularly suitable for high-frequency and high-power applications. In this configuration, the horn is fed through a waveguide port, ensuring efficient coupling and mode purity [6].

- **Advantages:**

- Maintains high mode purity, typically exciting only the fundamental mode.
- Supports both linear and circular polarization with appropriate waveguide configurations.
- Scalable for higher frequencies, including millimeter-wave systems.

- **Practical Implementation:**

The attached document notes the use of a **waveguide port** for feeding the antenna, emphasizing its role in achieving consistent and reliable performance

2.4.3. Orthogonal Waveguide ports for Circular Polarization

For circular polarization, two orthogonal waveguide feeds can be employed. These feeds are driven in **phase quadrature** (90° phase difference), ensuring equal excitation of orthogonal components of the electric field.

- **Applications:**

- Satellite tracking systems, where polarization purity and rotational symmetry are essential.
- Radar systems that require circular polarization to reduce clutter and improve target detection.

- **Challenges:**

- Precision in phase control is critical for achieving accurate circular polarization [37].

2.4.4. Waveguide Feed Configurations

Waveguide feeds are versatile and can be adapted for various operational requirements by selecting the appropriate waveguide type and orientation:

a) **Rectangular Waveguide:**

- Excites a linearly polarized wave aligned with the waveguide's broad face.
- Simple and commonly used for linearly polarized systems.

b) **Circular Waveguide:**

- Supports both linear and circular polarization.
- Allows seamless transitions between different polarization states with minimal structural changes.

c) **Dual-Feed Waveguide System:**

- Combines two waveguides, often in a hybrid or orthogonal arrangement, to support dual-polarized or circularly polarized operation [37].

2.5. Performance Considerations

The choice of feed method impacts several performance metrics of the horn antenna:

- **Polarization Purity:** Circular polarization requires precise phase and amplitude control in the feed system.
- **Efficiency:** Waveguide feeds ensure efficient energy transfer and minimal reflection losses.
- **Beam Symmetry:** Proper feeding aligns the radiation pattern with the horn's geometric axis, reducing asymmetries.

2.5.1. Orthogonal Waveguide Ports for Circular Polarization

Horn antennas are renowned for their versatility, simplicity, and high-performance characteristics in a variety of applications, including communications, radar, and satellite systems. The performance of a horn antenna is typically evaluated based on its gain, beamwidth, pattern symmetry, and sidelobe levels. This report explores these performance parameters in detail, referencing findings from the attached document Horn Antennas.pdf, with a focus on how different profiles influence the radiation characteristics [24], [37].

2.5.2. Physical parameters

The geometric design parameters of the proposed antenna play a crucial role in determining its radiation characteristics and impedance matching. Essential factors such as the antenna's shape, size, and configuration are guided by the resonance mode of the dielectric material and the targeted radiation pattern. By optimizing these parameters, the antenna can achieve desired radiation properties, including high gain, focused radiation patterns, broad bandwidth, and reduced sidelobes [2].

The dimensions of the horn and lens were calculated using the model described in (Table 2.1). These calculations were specifically optimized for a center frequency of $f_0=160$ GHz. The physical characteristics of the horn and lens antennas are summarized in the following tables:

Table 2.1 Horn Dimensions

Horn Antenna		
Name	Description	Value
D_g	Waveguide diameter	1.199 mm
L_g	Waveguide length	1.499 mm
D_f	Flare diameter	6.807 mm
L_f	Flare length	7.852 mm
p	Power of the function used for the profile	1
A	Amount of profile added to linear taper	1
X	Device X-dimension	6.807 mm
Y	Device Y-dimension	6.807 mm
Z	Device Z-dimension	9.351 mm

p - profile power index

A - profile addition index

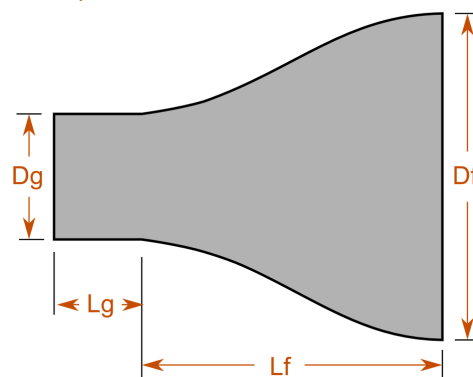


Figure 2.2. Horn side view

The antenna can be customized to attain specific gain values or 10 dB beamwidths in the E- and H-planes, with the objective of ensuring optimal axial pattern symmetry to meet the requisite specifications. While certain profiled horns exhibit enhanced pattern symmetry and reduced sidelobe levels in comparison to the linear conical horn, others do not demonstrate such enhancements. Among the profiles, the tangential and exponential designs have emerged as the most effective alternatives to the linear configuration.

2.6. Results and Discussion

The proposed horn antenna was designed and simulated using CST Microwave Studio. The improved performance of its parameters is solely attributed to the optimized geometric design of

2.6.1. Reflection Coefficient

The reflection coefficient results are shown in Figure 2.3. These results correspond to the geometric dimensions specified in the table above (Table 2.1)

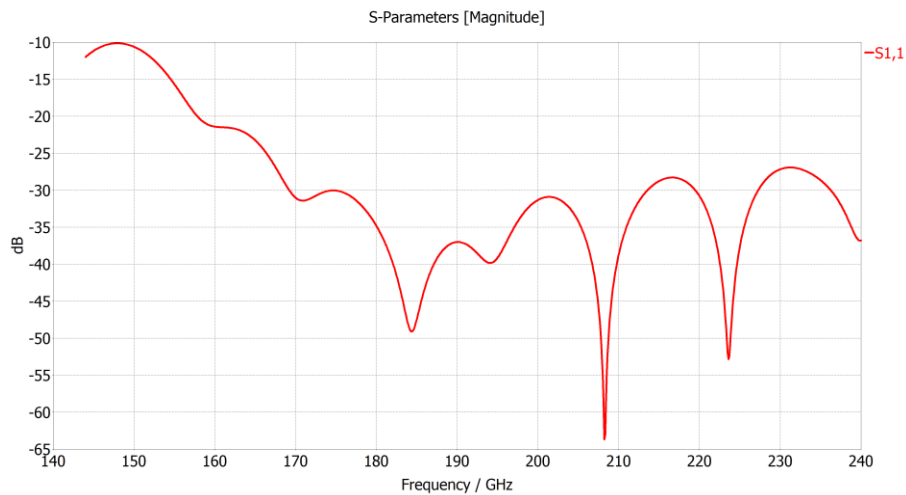


Figure 2.3. Magnitude of reflection coefficient

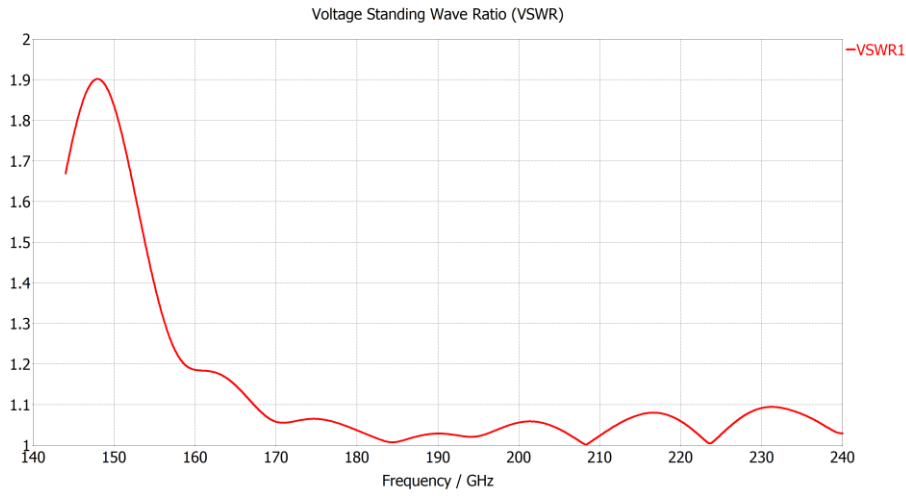


Figure 2.4. Voltage Standing Wave Ratio (VSWR).

It is evident that the reflection coefficient (S_{11}) decreases as the frequency increases. Throughout most of the studied frequency band, the S_{11} values remain below -10 dB, indicating excellent impedance matching for the antenna over this range [1], [33].

At a frequency of $f=147$ GHz, the S_{11} value is -10 dB. Beyond this frequency, S_{11} continues to decrease, reaching a minimum of -63 dB at 208 GHz. The proposed antenna achieves an S_{11} bandwidth equal to 100%, classifying it as nearly frequency-independent within this range.

Similarly, the results for the Voltage Standing Wave Ratio (VSWR) are consistent with the reflection coefficient across the same frequency band. The VSWR remains below 2 throughout the studied range, with a minimum value of 1 observed at 184 GHz, 208 GHz and 224 GHz (Figure 2.4). These results confirm the excellent impedance matching and validate the effectiveness of the proposed antenna design.

2.6.2. Radiation Pattern

The results of the reflection coefficient (Figure 2.3) indicate that the antenna is well matched. However, good impedance matching does not necessarily guarantee a uniform power distribution. To address this, the results of the radiation patterns (Figures 4 to 17) provide a deeper insight into the antenna's performance.

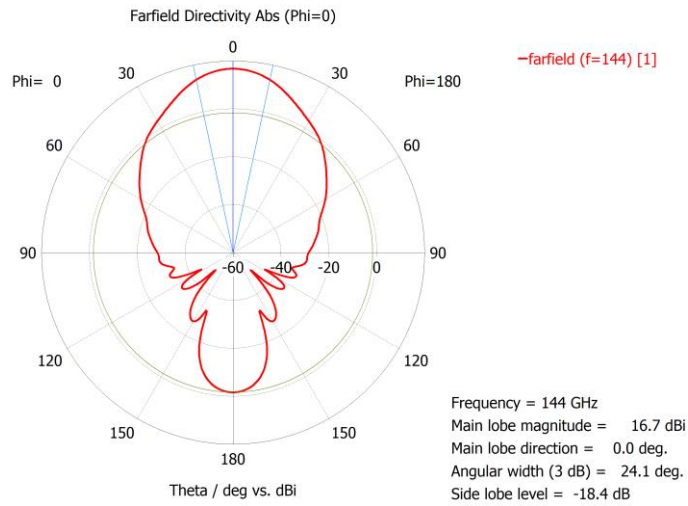


Figure 2.5. Radiation pattern at 144 GHz.

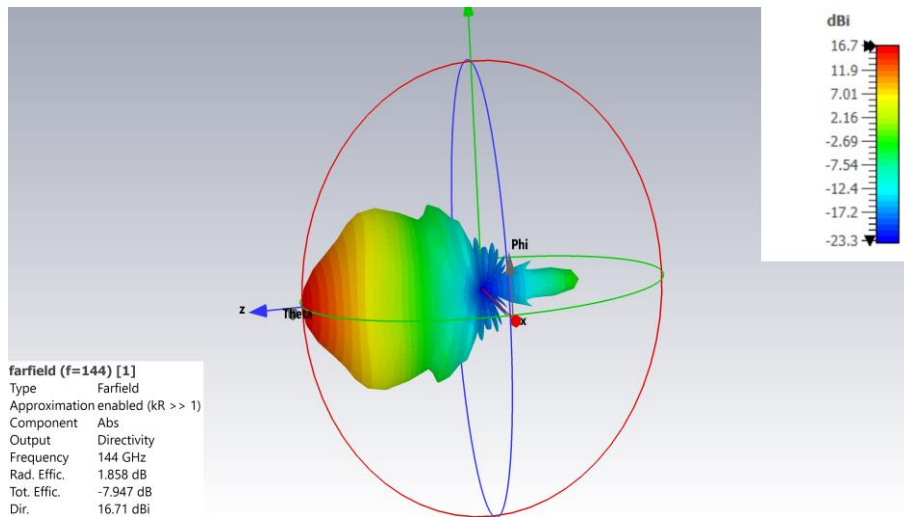


Figure 2.6. 3D Radiation pattern at 144 GHz.

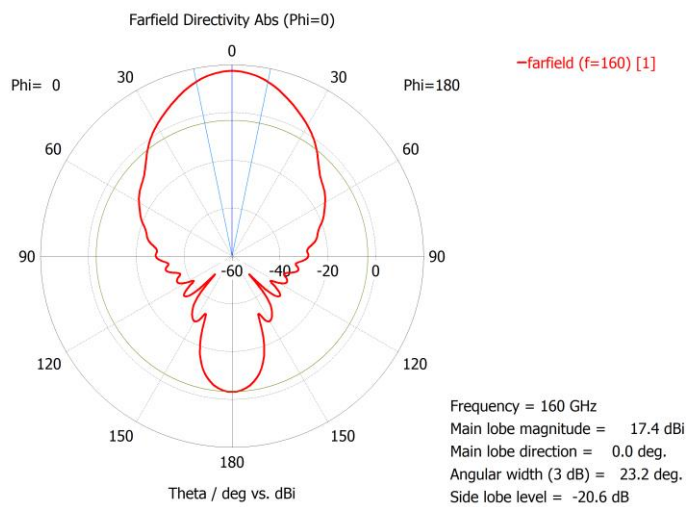


Figure 2.7. 2D Radiation pattern at 160 GHz

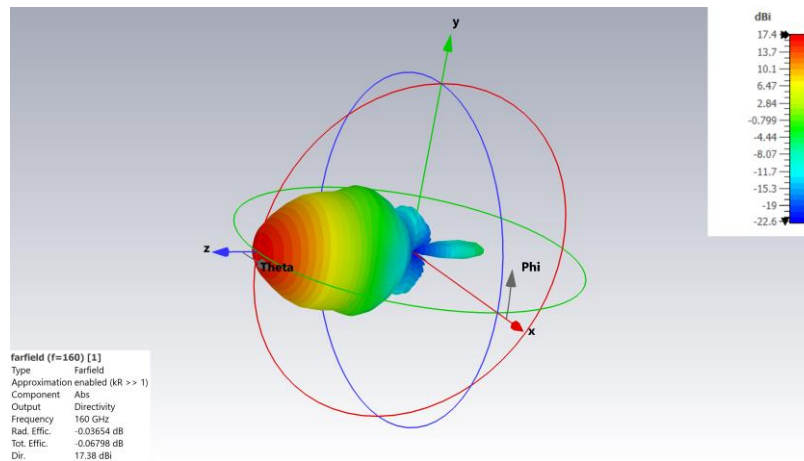


Figure 2.8. 3D Radiation pattern at 160 GHz.

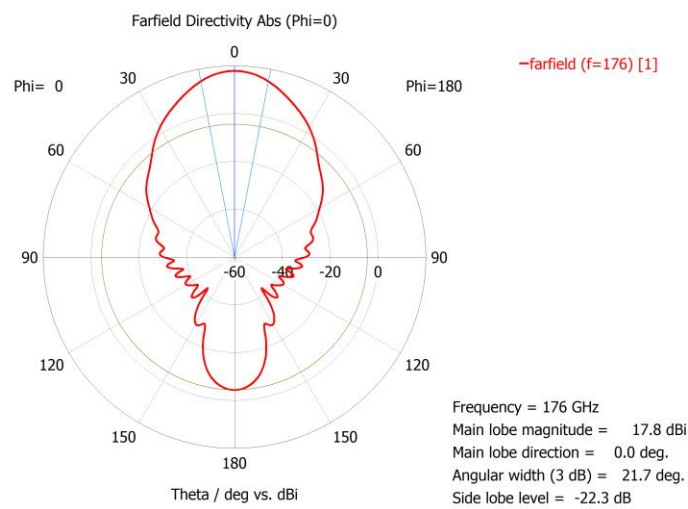


Figure 2.9. 2D Radiation pattern at 176 GHz

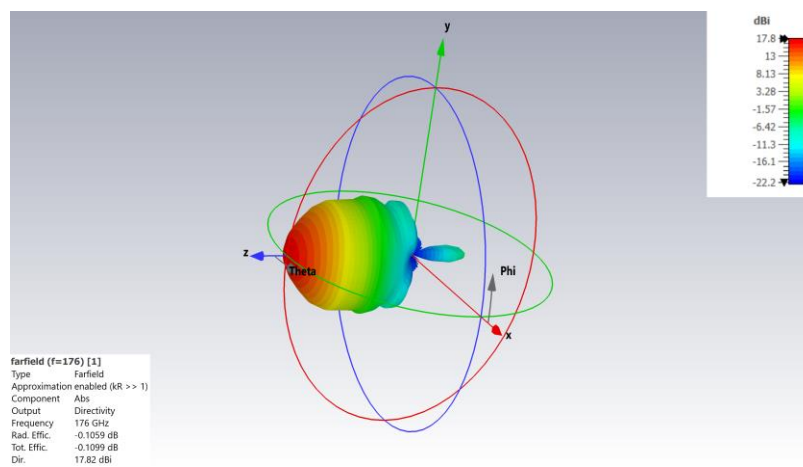


Figure 2.10. 3D Radiation pattern at 176 GHz.

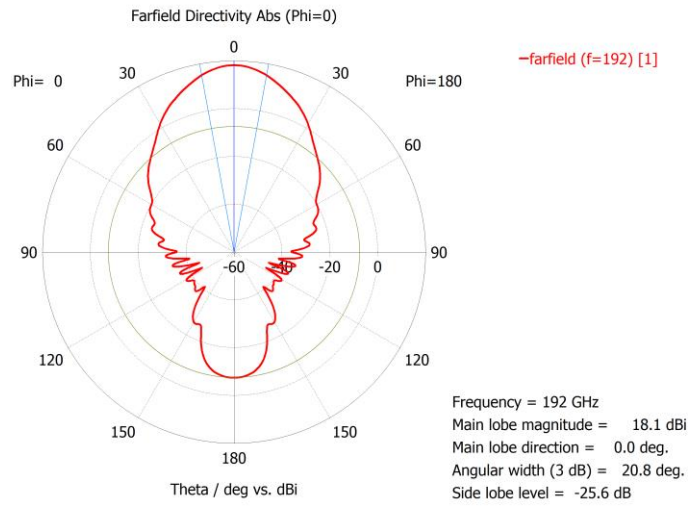


Figure 2.11. 2D Radiation pattern at 192 GHz

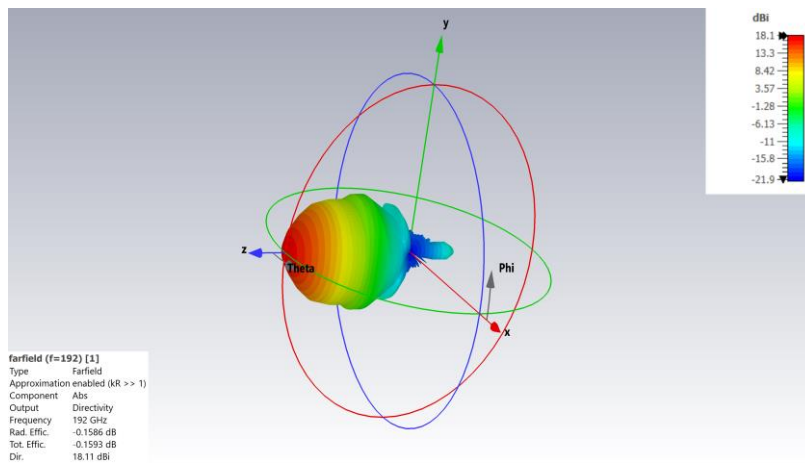


Figure 2.12. 3D Radiation pattern at 192 GHz.

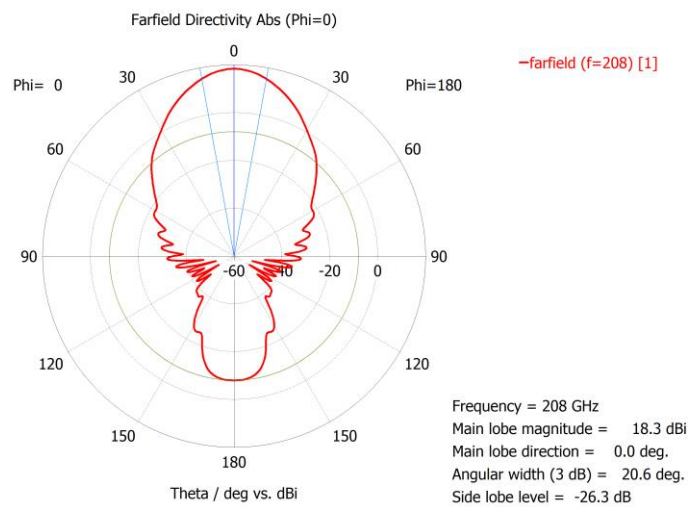


Figure 2.13. 2D Radiation pattern at 208 GHz

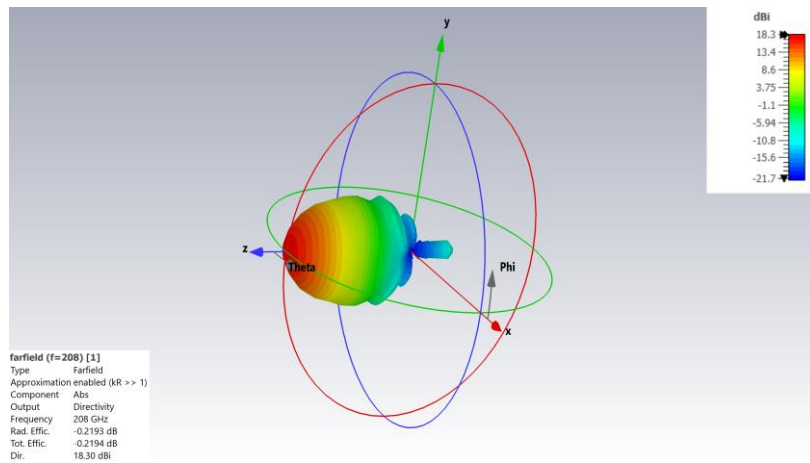


Figure 2.14. 3D Radiation pattern at 208 GHz.

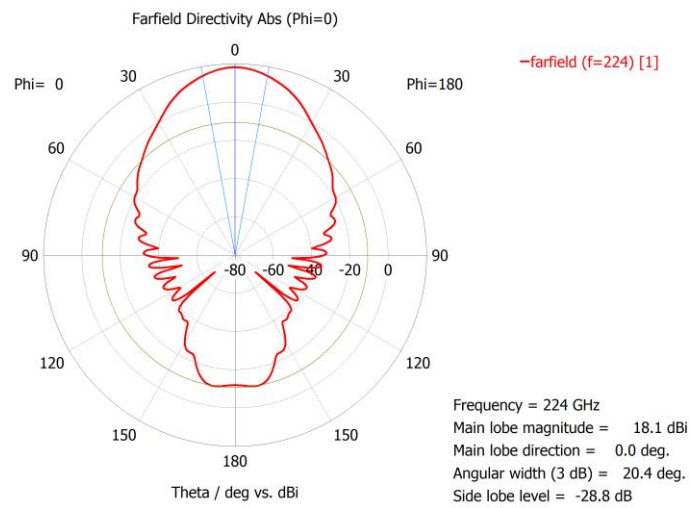


Figure 2.15. 2D Radiation pattern at 224 GHz

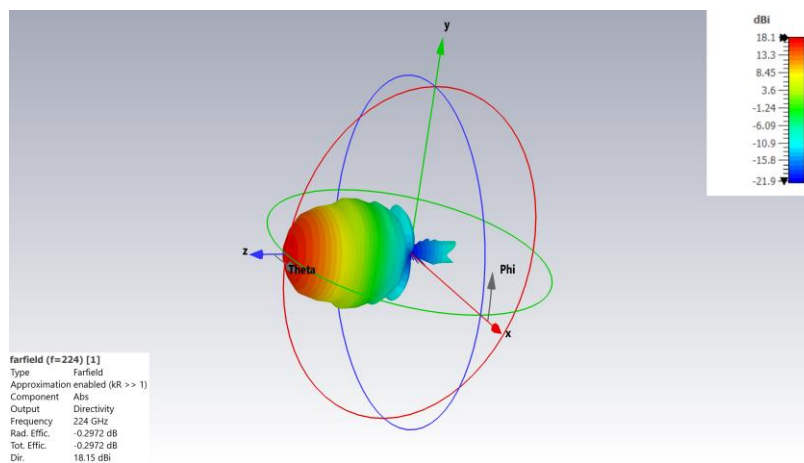


Figure 2.16. 3D Radiation pattern at 224 GHz.

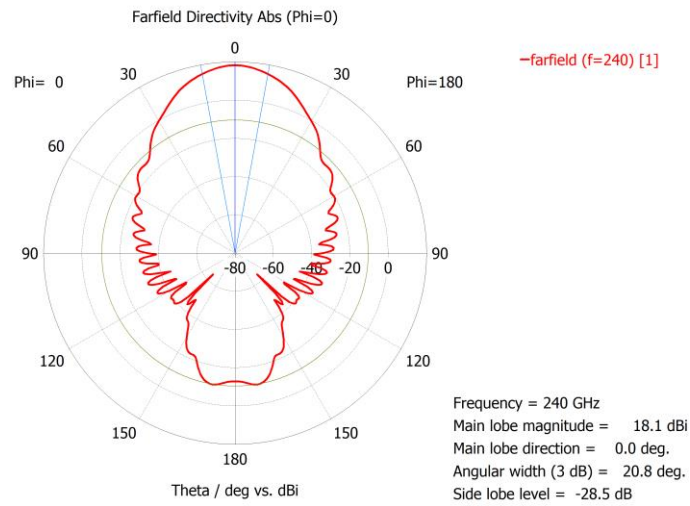


Figure 2.17. 2D Radiation pattern at 240 GHz

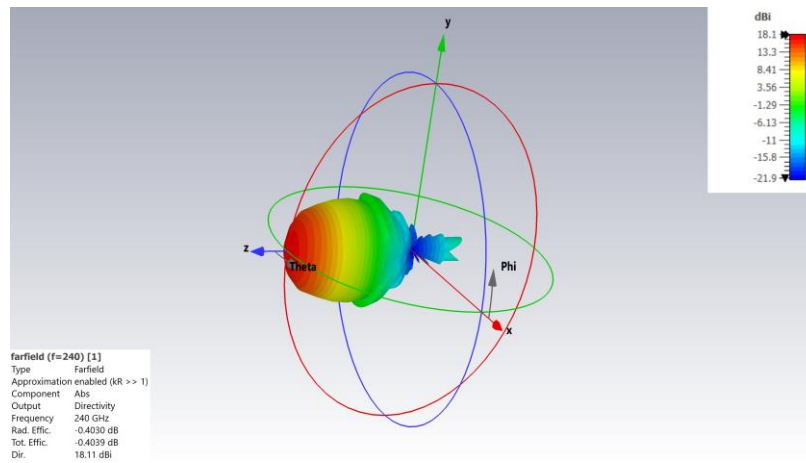


Figure 2.18. 3D Radiation pattern at 240 GHz.

The 2D and 3D radiation patterns of the antenna over a broad band centered at f_0 are presented in Figures 4 to 17. These figures demonstrate that the antenna attains gain values exceeding 16 dB within the 144 GHz to 240 GHz frequency range, with a maximum gain of 18.3 dB at the center frequency of 208 GHz. Beyond this frequency range, the gain undergoes a slight decrease, yet remains above 18 dB for the remainder of the studied band.

2.7. Conclusion

The smooth-wall conical horn antenna (SWCHA) stands out as a pivotal element in microwave systems due to its simplicity, reliability, and versatility. The discussion has underscored its suitability for various polarization modes, particularly in critical applications such as satellite communications, radio astronomy, and radar systems. Despite its straightforward design and manufacturing advantages, SWCHA faces performance challenges that need addressing for high-precision use cases.

Profiling the flare of the SWCHA has emerged as an effective method to enhance its performance, allowing for better control of mode conversion, improved radiation pattern symmetry, and reduced sidelobe levels. However, the limitations in cross-polarization suppression and the complexity of combining multiple profiles indicate that SWCHA cannot completely replace more intricate designs like corrugated horns in all applications.

The various feeding methods, particularly waveguide feeds and coaxial probe systems, have been evaluated for their impact on the horn antenna's performance, emphasizing the need for precise phase and amplitude control to ensure polarization purity and efficient energy transfer. Overall, the study confirms that with optimized design parameters, the SWCHA can achieve impressive impedance matching and radiation characteristics over a broad frequency band, maintaining a high gain even at higher frequencies. These findings advocate for the continued use and further enhancement of smooth-wall horns in a variety of microwave applications, balancing performance with cost-effectiveness.

Chapter 3. Dielectric Lens Antennas Modeling and Design

3.1. Introduction

This chapter explores the principles behind the design and integration of dielectric lens antennas, highlighting key factors such as material selection, geometric configuration, and fabrication techniques. We will examine how these factors contribute to improving antenna performance, especially in terms of gain, directivity, and efficiency. Furthermore, the chapter will review the advancements in dielectric lens antenna technology, providing insights into current research trends and future prospects in antenna design [27], [38].

3.2. Fundamentals of Dielectric Lenses

Dielectric lenses have emerged as a key enabler in the advancement and optimization of antenna systems, particularly in high-frequency domains like microwave, millimeter-wave, and terahertz applications. These lenses are engineered to manipulate electromagnetic waves through the principle of refraction, a process that alters the wave's direction and shape as it passes through the lens material. By varying the refractive index and the geometry of the lens, dielectric lenses control the wave's propagation, enabling precise management of the wave's focus, direction, and spread [29].

The process of wave manipulation is fundamentally similar to the way optical lenses control light, as both utilize refraction to shape the wave's propagation. In dielectric lenses, the same refractive principles are extended to electromagnetic waves across different frequencies. By altering the lens's geometry, including its curvature and profile, engineers can precisely direct the propagation of waves into desired patterns. This control plays a key role in maximizing directivity, gain, and beamforming, which are essential for the performance of systems in satellite communications, radar, and high-frequency wireless technologies [39].

3.2.1. Principle of Electromagnetic Wave Refraction

Dielectric lenses work by altering the direction of electromagnetic waves through refraction, a process governed by the refractive index of the material. The refractive index is defined as:

$$n = \frac{c}{v} \quad (3.1)$$

where:

- c is the speed of light in a vacuum,
- v is the speed of light in the dielectric material.

This change in the speed of propagation alters the wave's direction and can be used to focus or shape the beam [33].

3.2.2. Dielectric Material Properties

The choice of dielectric material in antenna design plays a critical role in determining the performance of the antenna, especially in high-frequency applications. Dielectric materials, which are non-conductive substances, have the ability to affect the electromagnetic wave propagation through their electric properties. These materials influence parameters like dielectric constant, loss tangent, permittivity, and thermal stability, all of which impact the efficiency, bandwidth, and overall performance of antennas [39], [27].

3.2.2.1. Dielectric Constant (Relative Permittivity)

The dielectric constant (ϵ_r) is a key property that describes how a material affects the electric field within it. It measures the material's ability to store electrical energy in an electric field. A higher dielectric constant allows for more effective focusing of electromagnetic waves, leading to smaller and more compact antenna designs. However, a high dielectric constant can also increase the material's loss, particularly at high frequencies.

For example, materials with high dielectric constants, like **Teflon** (with a dielectric constant around 2.1), are often used for antenna substrates because they provide good wave manipulation without excessively increasing the size of the antenna. On the other hand, materials with low dielectric constants may be favored for applications requiring lower losses and higher efficiency, as they tend to exhibit less attenuation of electromagnetic waves.

Impact on Performance: A higher dielectric constant typically results in a more compact antenna, but this may also come with higher losses in signal transmission, especially in high-frequency systems [3], [39].

3.2.2.2. Loss Tangent ($\tan \delta$)

The loss tangent ($\tan \delta$) of a dielectric material quantifies the energy loss as electromagnetic waves pass through it. It is defined as the ratio of the material's resistive loss to its reactive power. A low loss tangent is critical for applications that require high efficiency, such as in communication and radar systems, where signal attenuation must be minimized.

Materials with a low loss tangent, such as quartz or PTFE, are ideal for high-performance antenna applications. These materials help reduce energy dissipation, allowing for longer-range communication and improved signal integrity [21].

Impact on Performance: A low loss tangent ensures that the antenna can operate with minimal energy loss, thus improving the antenna's efficiency, especially at higher frequencies.

3.2.2.3. Conductivity (σ)

Conductivity (σ) is a fundamental material property that measures the ability of a substance to conduct electric current, expressed in siemens per meter (S/m). In antenna design, it significantly affects performance in both conductive and dielectric materials. High conductivity is desirable for radiating elements and ground planes, where metals like copper or aluminum are used to minimize resistive losses, thereby improving efficiency and gain. Conversely, dielectric materials in substrates should have very low conductivity to avoid dielectric losses that can reduce radiation efficiency. The loss tangent, which quantifies these losses, depends on both the conductivity and the operating frequency [21].

Optimal antenna performance requires careful selection of materials with high conductivity for conductive elements and low conductivity for dielectric substrates to ensure minimal power dissipation and maximal radiation efficiency [40], [41].

3.2.2.4. Temperature Stability

Temperature stability in antenna design refers to a material's ability to maintain its dielectric properties, particularly the dielectric constant (ϵ_r) and loss tangent ($\tan \delta$), across a range of temperatures. This stability is critical for ensuring consistent antenna performance. Variations in the dielectric constant can cause shifts in the resonant frequency, leading to detuning and reduced efficiency, while an increase in the loss tangent results in higher energy

dissipation and lower radiation efficiency. Poor temperature stability compromises bandwidth, gain, and overall reliability. To mitigate these effects, materials with a low temperature coefficient of permittivity (τ_ϵ) are preferred, as they minimize frequency drift and performance degradation. High-performance dielectric materials such as ceramics, PTFE (Teflon), and advanced substrates like Rogers RO4000 series are designed for excellent thermal stability. Selecting thermally stable materials ensures antennas operate reliably under diverse environmental conditions, maintaining optimal frequency response, bandwidth, and efficiency, making temperature stability a vital consideration in high-precision antenna design [22].

3.3. Design Considerations

When designing dielectric lens antennas, several key considerations must be addressed to optimize performance, efficiency, and suitability for specific applications. These considerations include:

3.3.1. Material Selections

- **Dielectric Constant and Loss Tangent:** The choice of dielectric material significantly impacts the lens's performance. A material with a high dielectric constant (ϵ_r) helps reduce the size of the lens, whereas a low loss tangent ($\tan \delta$) ensures minimal energy dissipation, thus maximizing efficiency. Materials such as PTFE (Teflon), ceramics, and specialized polymers are commonly used for their favorable dielectric properties and low loss characteristics.
- **Temperature Stability:** The dielectric properties of materials can vary with temperature, affecting the antenna's performance. Materials with stable dielectric constants across temperature variations are essential to prevent frequency drift and ensure reliable operation in varying environmental conditions [32].

3.3.2. Lens Geometry and Shape

- **Focal Length and Beamwidth:** The geometry of the dielectric lens is critical in determining its focal length and the beamwidth of the antenna. Lenses with a shorter focal length tend to concentrate the energy in a narrower beam, offering higher directivity and gain. The shape—whether hyperbolic, elliptical, or parabolic—will

dictate the lens's ability to focus the electromagnetic waves efficiently and the resulting radiation pattern.

- **Curvature and Thickness:** The curvature of the lens plays a key role in shaping the radiation pattern, especially in terms of how sharply the beam is focused. Thinner lenses typically offer better performance in terms of minimizing diffraction losses, but they may be more difficult to manufacture and less durable than thicker designs [38], [8].

3.3.3. Frequency Range and Bandwidth

- **Design Frequency:** The lens must be designed for the specific operating frequency range of the antenna system. At higher frequencies, the wavelength becomes shorter, requiring smaller lenses. Bandwidth is another important consideration—certain lens types, such as gradient-index (GRIN) lenses, can maintain efficiency over a broader frequency range, while others may only perform well at a narrow set of frequencies.
- **Dispersion Effects:** The dielectric material's behavior must be considered to minimize dispersion (the frequency-dependent change in wave velocity), which can distort the wavefronts and degrade performance, especially in wideband applications [5].

3.4. Modeling Technique

In the design and analysis of dielectric lens antennas, the use of CST Studio Suite offers a powerful and sophisticated platform for simulating complex electromagnetic behavior. However, achieving precise and reliable results requires more than simply running standard simulations; it demands the implementation of advanced modeling techniques, careful calibration of simulation parameters, and a deep understanding of how material properties, boundary conditions, and solver configurations affect antenna performance. Given the sensitivity of dielectric materials to frequency, temperature, and geometric variations, meticulous attention to these factors is crucial to ensure the fidelity of the results [42].

3.4.1. Electromagnetic Solvers

3.4.1.1. *Time Domain Solver*

The Time Domain Solver operates by directly solving Maxwell's equations in the time domain, using discrete time steps to calculate the electric and magnetic field values at each spatial point. This simulation approach allows for the observation of field dynamics over time, which is crucial for understanding wave propagation, signal interactions, and energy transfer through materials.

- **Time Stepping:** The solver divides time into discrete steps and iteratively calculates the electromagnetic fields at each point in space at every step. This allows for accurate simulation of transient behaviors and broadband responses.
- **Field Propagation:** The solver tracks how the electric and magnetic fields propagate through the model, providing insights into how energy flows and interacts with structures, such as dielectric lens antennas [43], [44].

3.4.1.2. *Frequency Domain Solver*

The Frequency Domain Solver works by solving the electromagnetic fields in the frequency domain for a given structure. The problem is solved for a range of frequencies, usually focusing on one or a few discrete frequencies at a time. The solver computes the steady-state behavior of the system, making it suitable for analyzing resonant frequencies, transmission lines, filters, and other structures where narrowband behavior is important [45].

- **Harmonic Solution:** The solver assumes sinusoidal (harmonic) excitation at a given frequency and finds the solution in the frequency domain, where the fields do not change with time but are periodic.
- **Frequency Sweep:** It can perform a frequency sweep across a specific range, allowing for the study of how a structure behaves at different frequencies (resonance, scattering, impedance, etc.).

3.4.2. Meshing Technique

3.4.2.1. *Hexahedral Meshing*

A hexahedral mesh is a type of structured mesh consisting of hexahedral elements, or bricks, which are six-sided polyhedra with rectangular faces. This mesh is widely used in computational simulations, including electromagnetic modeling, due to its inherent structure

and efficiency in certain geometries. In the context of electromagnetic simulations, such as those performed with CST Studio Suite, hexahedral meshes are commonly applied to simplify the meshing process, particularly when the geometry is regular and well-aligned with the Cartesian coordinate system [43].

3.4.2.2. *Tetrahedral Meshing*

Tetrahedral meshing is a highly flexible and effective method for discretizing complex geometries in computational simulations, particularly when dealing with irregular or curved structures. Unlike hexahedral meshing, which uses structured, rectangular elements, tetrahedral meshing employs tetrahedra, pyramid-shaped elements characterized by four triangular faces, four vertices, and six edges. This meshing technique excels in handling geometries that do not conform to a regular grid, such as curved surfaces, intricate dielectric structures, and irregular shapes. As a result, it is particularly well-suited for modeling dielectric lens antennas, where such complex geometries are often present [1].

3.4.3. Combining Near-Field and Far-Field Analysis

Combining both near-field and far-field analyses provides a complete understanding of the dielectric lens antenna's performance.

- **Near-Field Design Optimization:** Near-field simulations help refine the design of the dielectric lens by evaluating how the geometry and material properties affect the wavefront inside the lens. This ensures that the antenna can focus and shape the wave properly.
- **Far-Field Performance Validation:** Far-field analysis validates the final radiation pattern and performance of the antenna, ensuring that it meets the desired specifications for applications such as communication, radar, or satellite systems [25], [10].

3.5. Simulations and results

The proposed dielectric lens has ellipsoid shape (Figure 3.1). This geometry is chosen due to its ability to efficiently focus electromagnetic waves and generate a highly directional beam. The selected shape provides an optimal balance between focusing the waves and minimizing diffraction losses, making it suitable for high-performance applications.

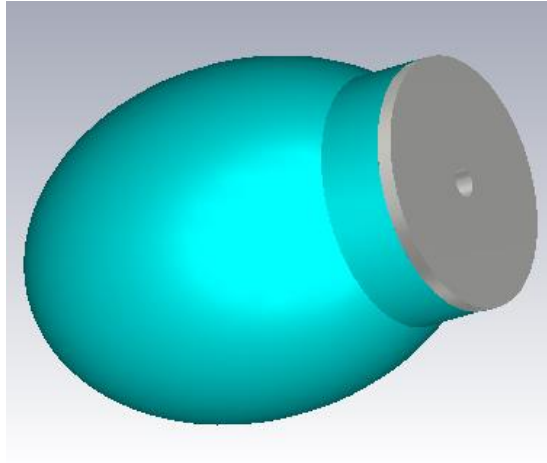


Figure 3.1. The proposed Dielectric Lens antenna

The dimensions of the lens play a critical role in achieving the desired focusing and beamforming characteristics. The lens diameter and focal length were carefully selected to strike an optimal balance between compactness and performance. While a larger lens diameter generally enhances resolution and gain, it also leads to an increase in system size and complexity. In this design, the lens diameter was chosen as (**Table 3.1**), ensuring it is large enough to effectively collect and focus electromagnetic waves, yet compact enough for practical integration into the antenna system.

Table 3.1. the proposed Dielectric Lens antenna Dimensions

Lens Antenna					
Name	Description	Value	Name	Description	Value
D_g	Waveguide diameter	2.498 mm	ϵ_r	Relative permittivity	2.08
L_g	Waveguide length	6.745 mm	X	Device X-dimension	28.77 mm
D_t	Transformer diameter	1.249 mm	Y	Device Y-dimension	28.77 mm
L_t	Transformer length	874.4 μm	Z	Device Z-dimension	37.26 mm
W_f	Flange width	1.249 mm	D_f	Flange diameter	22.20 mm
D_d	Dielectric diameter	28.77 mm	L_d	Dielectric length	30.51 mm

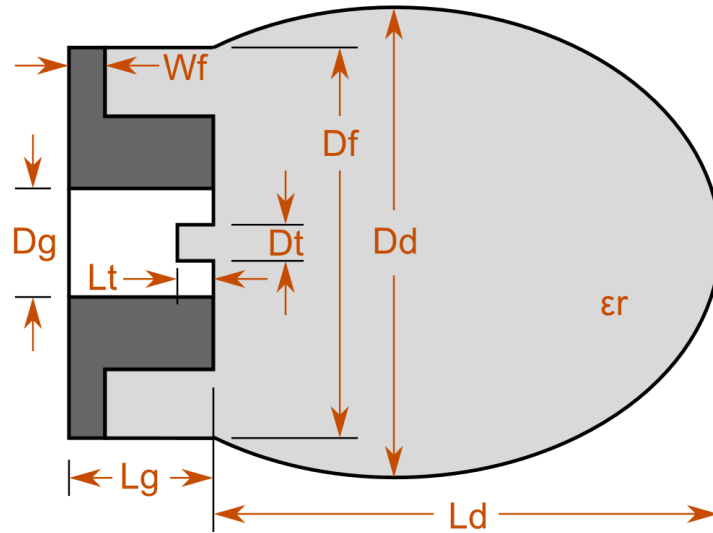


Figure 3.2. Dielectric Lens Antenna Side view

The axial symmetry of the dielectric lens and cylindrical waveguide antennas allows them to accommodate multiple polarization modes, including circular polarization. Linear polarization can be achieved by feeding the antenna with either a single coaxial probe or a waveguide. In this design, the cylindrical waveguide serves as the feed for the antenna, powered through a circular waveguide port (**Figure 3.3**) to ensure efficient energy transfer and precise polarization control.

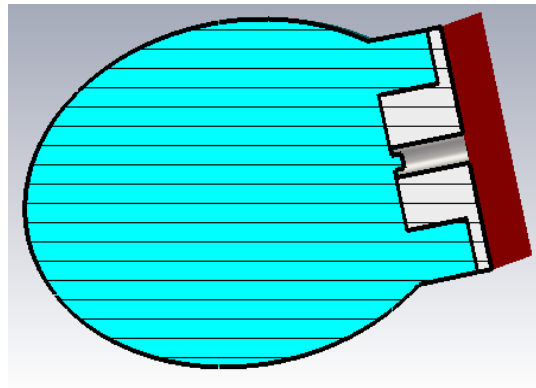


Figure 3.3. Cross section of dielectric lens and cylindrical waveguide antennas.

3.5.1. Reflection Coefficient

Across the entire frequency range of interest (greater than 144 GHz), the input reflection coefficient remains consistently below -15 dB, representing a significant improvement over the initial S11 value of -10.00 dB. This low reflection coefficient signifies highly efficient power

transfer, reduced signal loss, and superior impedance matching at the input, all of which are key factors in optimizing the overall performance of the antenna system. Additionally, the reflection behavior exhibits excellent transient characteristics, enhancing both system stability and dynamic responsiveness.

This combination of attributes is critical for enabling reliable monostatic radar measurements, particularly when detecting objects with small radar cross-sections located near the antenna. The minimal reflection and superior transient response reduce signal distortions, ensuring accurate target detection, precise distance measurement, and robust performance in challenging scenarios. The low-reflection profile minimizes interference and enhances the clarity of the received signal, which is essential for maintaining high accuracy and improved resolution.

Furthermore, the consistently low reflection across a wide frequency band supports a broad range of high-frequency applications, from precision sensing and high-resolution radar imaging to advanced communication systems that demand reliable performance, minimal degradation, and high signal fidelity. The optimized reflection coefficient directly contributes to the antenna's enhanced gain, beamforming precision, and overall efficiency, making it a vital parameter in achieving superior system reliability and performance for cutting-edge radar and communication technologies.

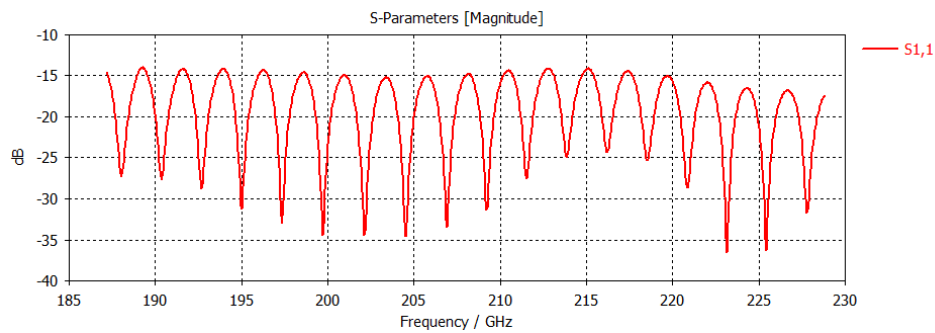


Figure 3.4. (S11) of the Proposed Dielectric antenna fed by a circular waveguide.

3.5.2. Voltage Standing Wave Ratio (VSWR)

In the proposed antenna system, achieving a Voltage Standing Wave Ratio (VSWR) of less than 1.5 reflects excellent impedance matching between the feed line and the dielectric lens antenna. This low VSWR indicates that the majority of the input power is efficiently transmitted

to the antenna with minimal reflection, resulting in reduced power loss and enhanced overall system performance. A VSWR of less than 1.5 also corresponds to a return loss greater than -14 dB, signifying superior signal integrity and minimal interference. This is crucial for maintaining stable and accurate performance in high-frequency applications, particularly in radar systems where precise detection and minimal distortions are essential. Additionally, improved impedance matching reduces thermal stress on components, contributing to greater system reliability and extended operational lifespan. By ensuring efficient power transfer and optimized antenna performance, the low VSWR enhances gain, directivity, and beam quality, making it a key factor in achieving robust and precise operation across the entire frequency band of interest.

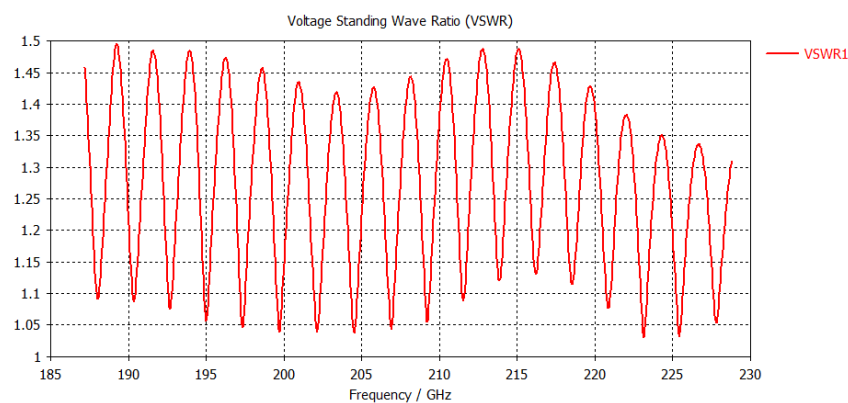


Figure 3.5. Voltage Standing Wave Ratio (VSWR).

3.5.3. Radiation Pattern

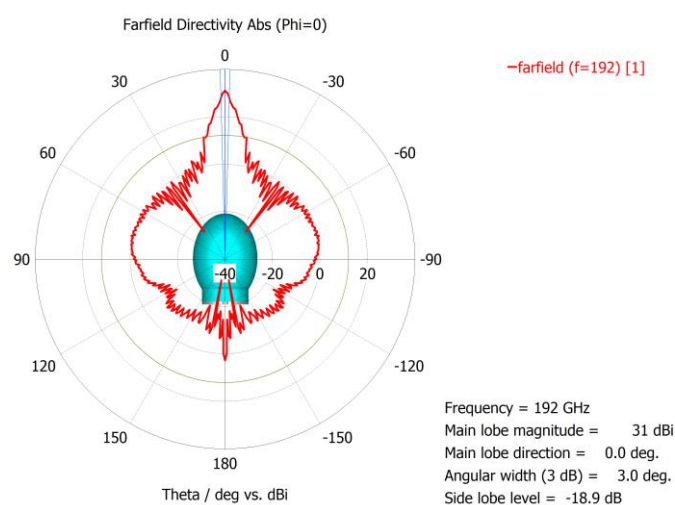


Figure 3.6. 2D Radiation pattern at f=192 GHz.

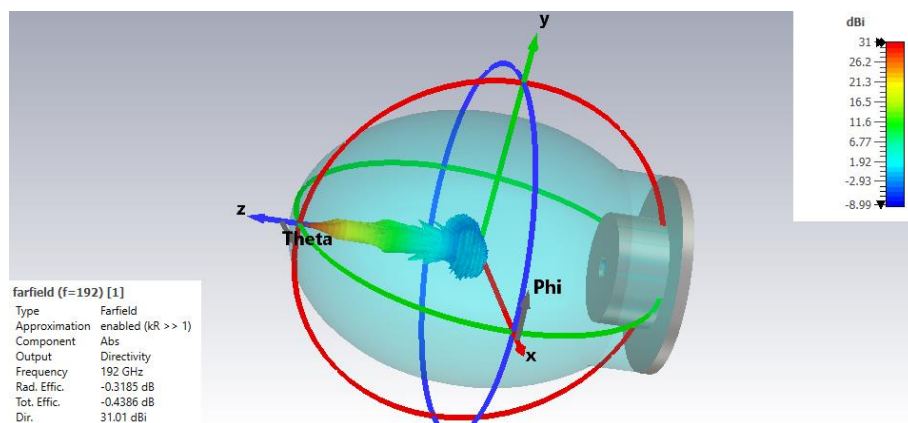


Figure 3.7. 3D Radiation pattern at f=192 GHz.

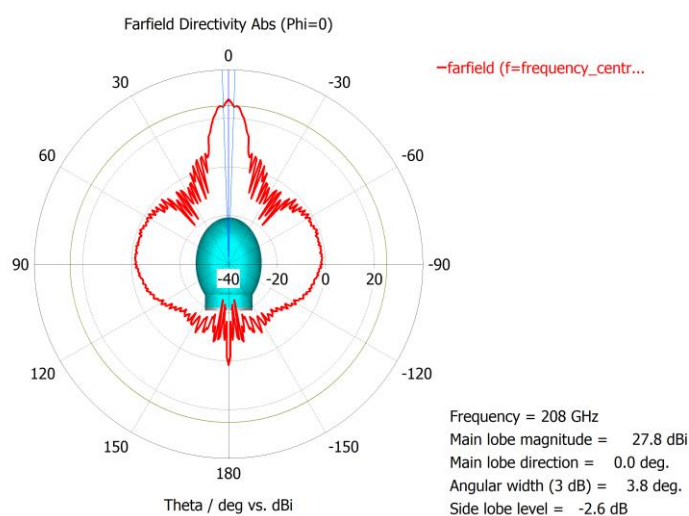


Figure 3.8. 2D Radiation pattern at f=208 GHz.

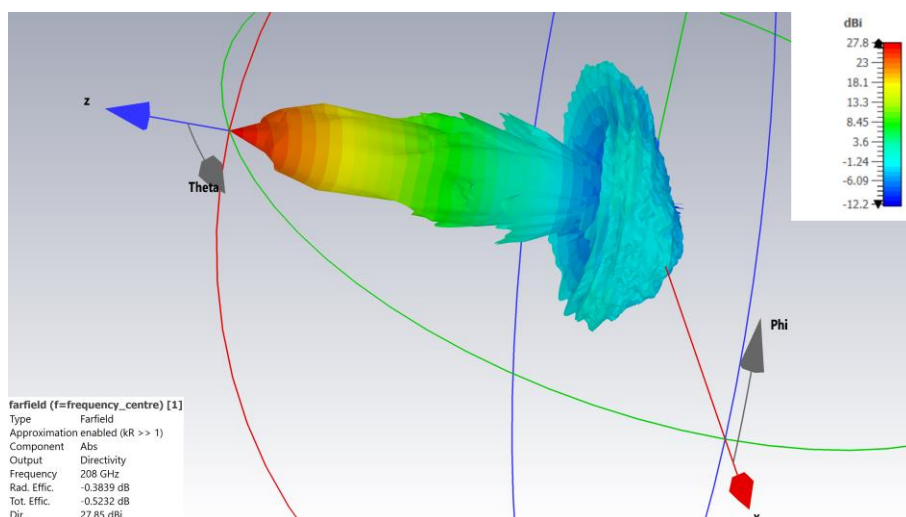


Figure 3.9. 3D Radiation pattern at f=208 GHz.

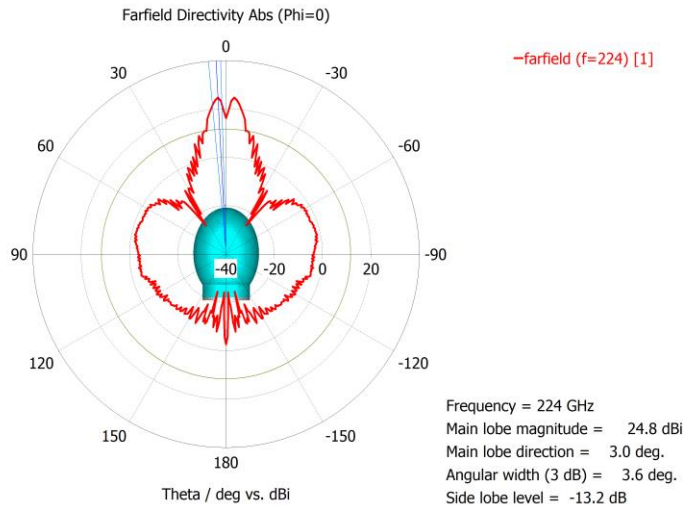


Figure 3.10. 3.11 2D Radiation pattern at f=224 GHz.

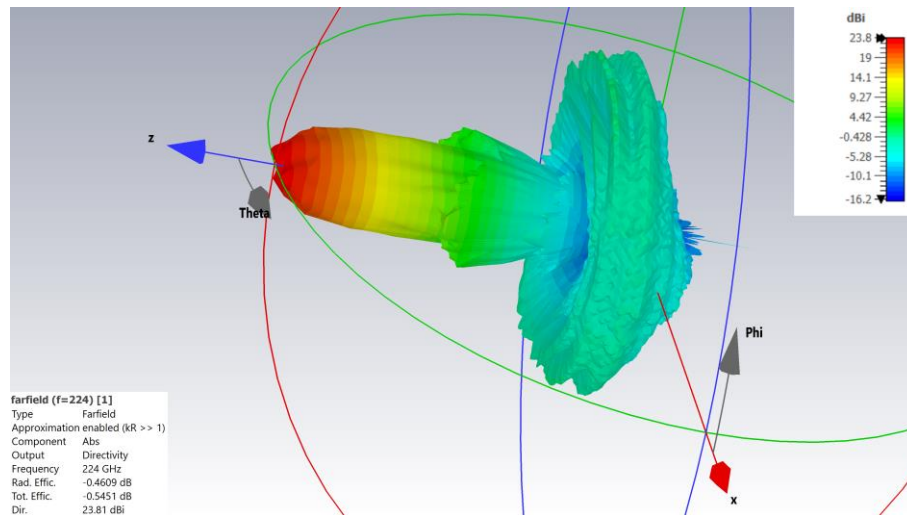


Figure 3.12. 3D Radiation pattern at f=224 GHz.

3.6. Conclusion

Dielectric lens antennas offer significant advantages in terms of gain, efficiency, and directivity, making them ideal for high-frequency applications where performance is critical. As the demand for faster, more efficient communication systems grows, dielectric lens antennas are poised to play a central role in the development of next-generation wireless technologies. Continued research and innovation in material science, design techniques, and manufacturing processes will further unlock their potential in a wide range of applications.

Chapter 4. Associated Dielectric Lens with Horn Antenna

4.1. Introduction

The exponential growth in user demand has led to congested spectrum and high-power consumption in existing communication systems, necessitating innovative solutions for future generations of wireless technologies. Next-generation communication systems are poised to utilize wider frequency bands to support the high data transfer rates required for emerging applications. To address spectrum congestion, one promising approach is the adoption of high-frequency operation, which enables wideband transmission and significantly enhanced data rates.

Millimeter-wave and sub-millimeter-wave technologies have gained considerable attention for their ability to achieve high data transmission rates while focusing on a smaller number of receivers over narrow beam angles. As communication systems transition toward these higher frequencies, which extend into the gigahertz and terahertz ranges, the demand for highly efficient, compact, and high-performance antenna designs has intensified. These advancements are critical to unlocking the potential of high-frequency communication systems in applications such as 5G/6G networks, radar systems, and high-resolution imaging technologies [46], [47], [48], [49].

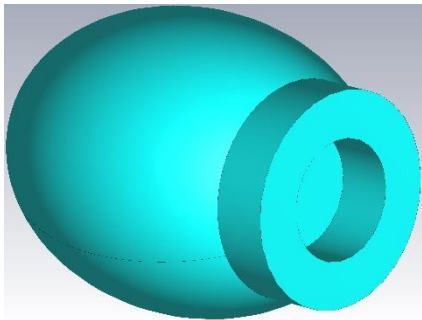
Among the myriads of antenna types, conical horn antennas and dielectric lens antennas have emerged as key players in various communication, radar, and sensing applications. While the conical horn antenna is renowned for its ease of fabrication and wide-band capabilities, the dielectric lens antenna stands out for its compactness and high focusing efficiency. Each of these antennas has distinct advantages and limitations when deployed in isolation. Compared with other form, the conical horns have shorter length and reduced weight. They are preferred for systems that prefer small mass and volume such as reflector systems that require a compact feed design. The conical horn has been favoured due to their simplicity, bandwidth, and ability to provide high radiation efficiency. In the literature, several high gain antennas and devices based conical horns have been proposed [40], [50], [34].

To optimize the antenna parameters, the integration of advanced techniques, such as profiled smooth conical horns has proven to be highly effective. The waveguide-fed profiled smooth conical horn is a horn antenna characterized by its gradual, smooth tapering from the waveguide to the open aperture. The key advantage of the profiled smooth conical design lies

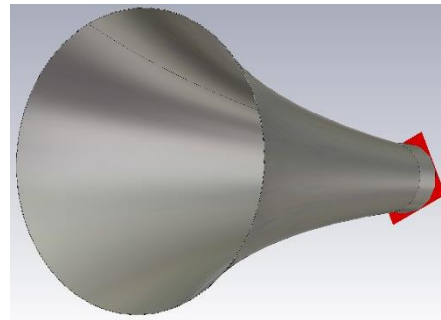
in its ability to produce a more uniform phase distribution at the aperture, reducing the side lobes and improving the main lobe directivity. This design, while already offering some degree of directivity enhancement, is often limited by diffraction effects at the aperture and the inherent impedance mismatch between the waveguide and the horn's open end. To address these limitations and further enhance the antenna's performance, the addition of a dielectric lens in front of the horn is a powerful solution [41], [51], [52], [53]. A dielectric lens serves to reshape and focus the radiation pattern, leading to an increased aperture efficiency by mitigating the spillover losses and reducing the loss of energy in side lobes. The dielectric lens works by altering the phase front.

4.2. Proposed Antenna Design

The design methodology for the proposed antenna system revolves around an efficient integration of the smooth-walled conical feed horn antenna and the dielectric lens to ensure optimal performance in terms of power transfer, thermal stability, and radiation characteristics (Figure 4.1).



(a) Dielectric Lens Antenna.



(b) Waveguide-Fed Profiled Smooth Conical Horn.

Figure 4.1. Schematic view of the proposed antenna.

The smooth-wall conical horn serves as the primary feed element, leveraging its robust radiation efficiency and capability to support the fundamental TE_{11} mode with minimal loss. The horn is meticulously profiled to achieve a gradual transition from the waveguide to its aperture, ensuring impedance matching and minimizing diffraction losses. This design step is critical for reducing sidelobe levels and enhancing the symmetry of the radiation pattern.

The dielectric lens is positioned strategically at the horn's aperture, with the objective of further refining the radiated beam by reshaping the phase front of the outgoing waves. This configuration ensures high aperture efficiency, as the lens focuses the energy radiated by the

horn into a tightly concentrated beam, improving directivity and reducing spillover losses. Special attention is given to the thermal management of the system to mitigate potential overheating issues, particularly at high frequencies where power densities can be significant.

The dielectric lens, typically constructed from low-loss materials with high thermal conductivity, aids in dissipating heat while maintaining performance stability. Precise alignment between the horn and the lens is achieved using advanced simulation tools such as CST Microwave Studio, which allows for detailed modeling and optimization of the entire antenna assembly. The simulation process involves iterative adjustments to key parameters, including the horn's flare angle, lens curvature, and dielectric constant, to achieve a harmonious balance between power transfer efficiency and radiation characteristics. This integrated approach not only enhances the overall gain and directivity of the proposed antenna but also ensures reliable operation under demanding conditions, making it well-suited for millimeter-wave applications such as radar, communication, and imaging systems [54].

4.2.1. Feed Method

The axial symmetry of the dielectric lens and conical horn antennas allows them to handle any polarization, including circular polarization. For achieving linear polarization, the antenna can be fed using a single coaxial probe or a waveguide. In this specific case, the antenna is fed by the conical horn, which itself is powered through a circular waveguide port (Figure 4.2).

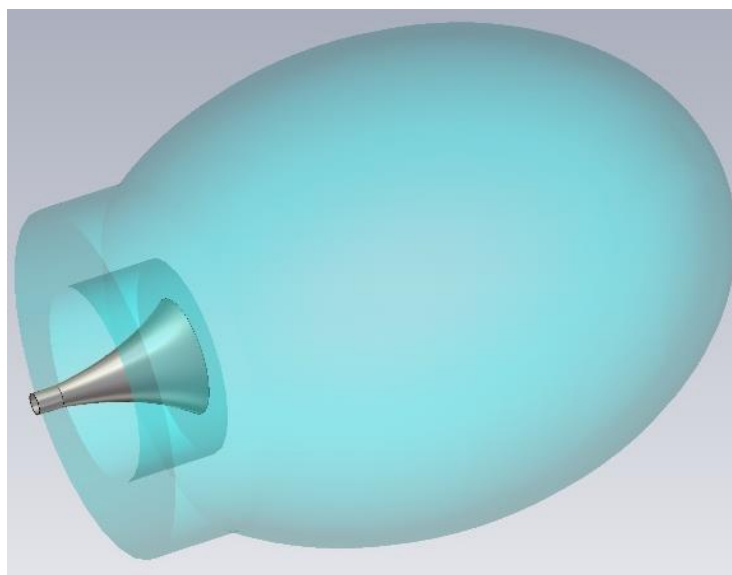


Figure 4.2. Proposed antenna: Dielectric lens feed by a conical horn.

The major limitation of this method is the idle time caused by the iterations effect, but it requires less resources compared to other techniques, which makes it more compatible with resource-limited systems [55]. The iterative system process is illustrated in (Figure 4.3).

4.2.2. Operational Mechanism

By properly relating the eccentricity of the dielectric lens to its dielectric constant and feeding the lens at one of its focal points using a conical horn, the majority of the rays are refracted in the forward direction, thereby constructing a planar phase front.

On the other hand, the lens interface can generate internal reflections, which significantly affect the input impedance and radiation characteristics. As expected, the physical optics (PO) contribution of doubly reflected rays is dominant in describing the input impedance. This is consistent with the geometric evidence that all rays emanating from a focal source return precisely to the origin after undergoing double reflection at the lens surface [45].

Using a lens material with a low relative permittivity (smaller than 3), the dielectric contrast with free space is typically low enough to neglect the effects of multiple internal reflections [46]. While additional matching layers can be employed to reduce reflections for materials with higher dielectric constants, they come at the cost of increased production complexity and expense [39]. For dense materials without such matching layers, internal resonances are excited within the lens, significantly affecting not only the input impedance but also the radiation properties. These effects manifest as reduced gain, beam distortions, and increased sidelobe levels [56].

4.2.3. Dielectric properties

The choice of substrate material plays a vital role in the design of dielectric lens antennas, as it significantly affects performance by reducing energy losses and improving efficiency. To minimize dissipation and enhance the antenna's overall functionality, a substrate with a low loss tangent ($\tan\delta$) is crucial.

In this study, Polytetrafluoroethylene (PTFE) was selected for its superior dielectric properties, featuring a low loss tangent of $\tan\delta=0.008$ and a relative permittivity of $\epsilon_r=2.08$. The use of PTFE in the proposed antenna design offers a promising solution for sub-THz

applications, thanks to its low energy loss and suitability for high-frequency requirements in sub-THz operations [38].

4.2.4. Physical parameters

The geometric design parameters of the proposed antenna play a crucial role in determining its radiation characteristics and impedance matching. Essential factors such as the antenna's shape, size, and configuration are guided by the resonance mode of the dielectric material and the targeted radiation pattern. By optimizing these parameters, the antenna can achieve desired radiation properties, including high gain, focused radiation patterns, broad bandwidth, and reduced sidelobes.

The dimensions of the horn and lens were calculated using the model described in [47,49]. These calculations were specifically optimized for a center frequency of $f_0=160$ GHz. The physical characteristics of the horn and lens antennas are summarized in the following tables:

Table 4.1. Lens antenna characteristics.

Lens Antenna					
Name	Description	Value	Name	Description	Value
D_g	Waveguide diameter	2.498 mm	ϵ_r	Relative permittivity	2.08
L_g	Waveguide length	6.745 mm	X	Device X-dimension	28.77 mm
D_t	Transformer diameter	1.249 mm	Y	Device Y-dimension	28.77 mm
L_t	Transformer length	874.4 μm	Z	Device Z-dimension	37.26 mm
W_f	Flange width	1.249 mm	D_f	Flange diameter	22.20 mm
D_d	Dielectric diameter	28.77 mm	L_d	Dielectric length	30.51 mm

Table 4.2. Horn antenna characteristics.

Horn Antenna					
Name	Description	Value	Name	Description	Value
D_g	Waveguide diameter	1.199 mm	A	Amount of profile added to linear taper	1
L_g	Waveguide length	1.499 mm	X	Device X-dimension	6.807 mm
D_f	Flare diameter	6.807 mm	Y	Device Y-dimension	6.807 mm
L_f	Flare length	7.852 mm	Z	Device Z-dimension	9.351 mm
P	Power of the function used for the profile	1			

4.3. Evaluation of the Obtained Results

The proposed antenna was designed and simulated using CST Microwave Studio software. The performance enhancement of its parameters is solely attributed to the optimized geometric design of the antenna.

4.3.1. Reflection Coefficient

The reflection coefficient results are presented in (Figure 4.3). These results correspond to a substrate with a relative permittivity of $\epsilon_r=2.08$ and a loss tangent ($\tan\delta$) of 0.008.

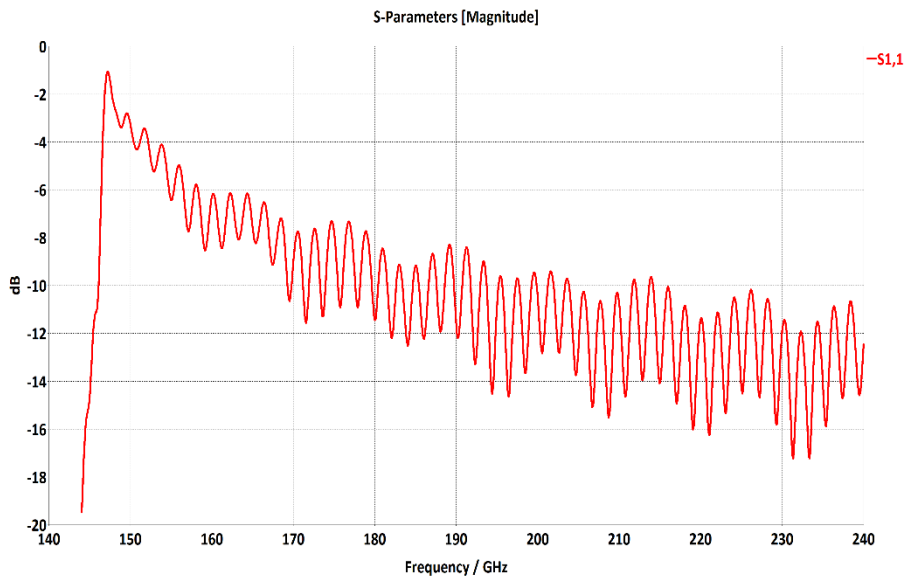


Figure 4.3. Iterative architecture process

It is observed that the reflection coefficient (S_{11}) decreases with increasing frequency. At $f = 170$ GHz, the initial value of $S_{11} = -10.00$ dB is recorded, reaching its minimum of $S_{11} = -14$ dB at 223GHz. This indicates improved impedance matching within this frequency range. The proposed antenna achieves an S_{11} bandwidth exceeding 35%, classifying it as nearly ultra-wideband (UWB).

4.3.2. Voltage Standing Wave Ratio (VSWR)

Similarly, the results for the Voltage Standing Wave Ratio (VSWR) are consistent with the reflection coefficient within the same frequency range. The VSWR remains below 2 from 170 GHz and achieves a minimum value of 1.4 at 210 GHz (Figure 4.4). These findings confirm the excellent impedance matching and validate the effectiveness of the proposed antenna design.

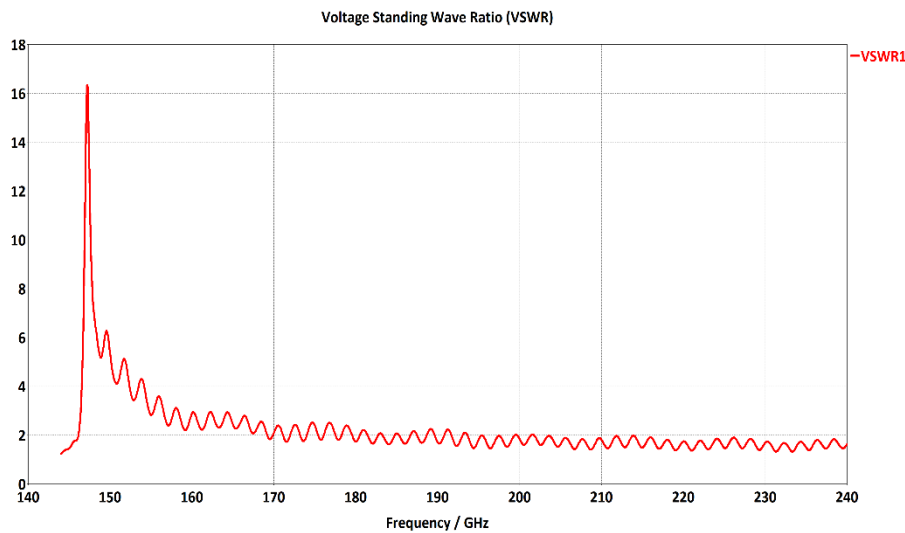


Figure 4.4. Voltage Standing Wave Ratio (VSWR).

4.3.3. Radiation Pattern

The reflection coefficient results (Figure 4.5) indicate that the antenna is well-matched. However, good impedance matching does not necessarily guarantee uniform power distribution. To address this, the radiation pattern results (Figure 4.5 to 18) provide deeper insights into the antenna's performance.

The 2D and 3D radiation patterns of the antenna at the central frequency (f_0) and its vicinity are illustrated in (Figure 4.5 to 16).

reveal that the antenna achieves remarkable gain values exceeding 33 dBi within the 160 GHz to 240 GHz band, with a peak gain of 36.3 dB at the central frequency of 240 GHz.

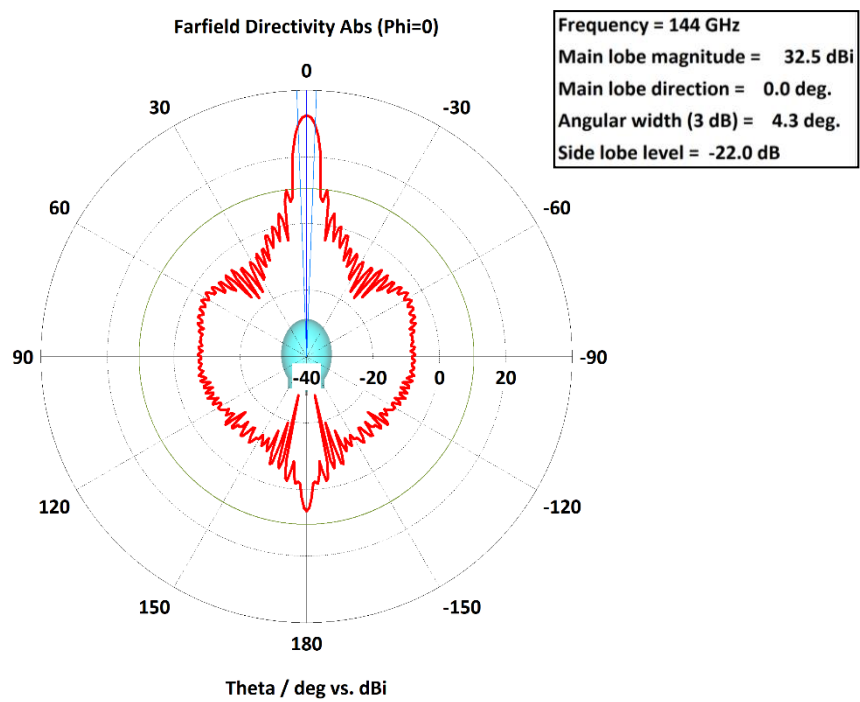


Figure 4.5. 2D Radiation pattern at f=144 GHz.

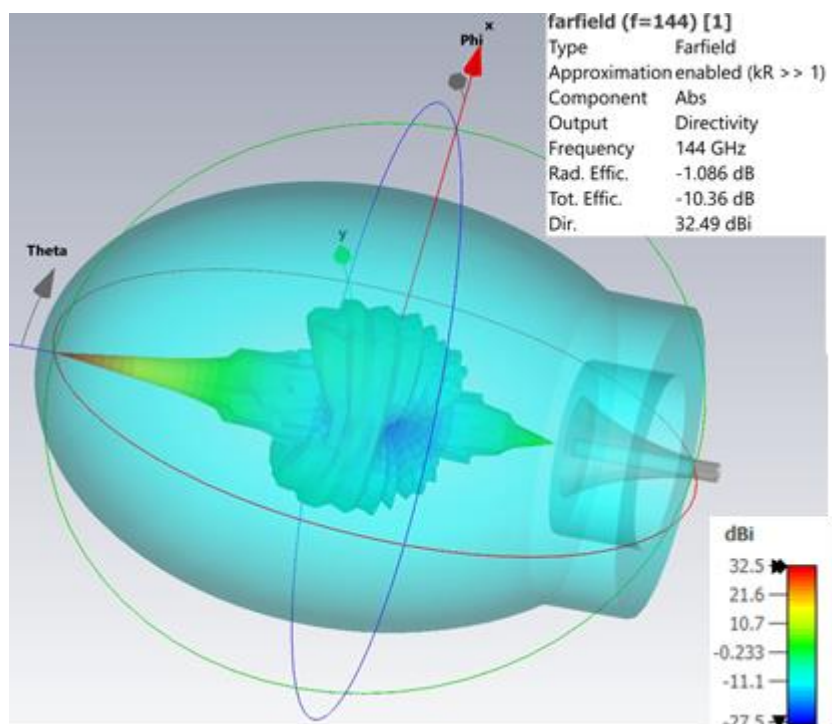


Figure 4.6. 3D Radiation pattern at f=144 GHz.

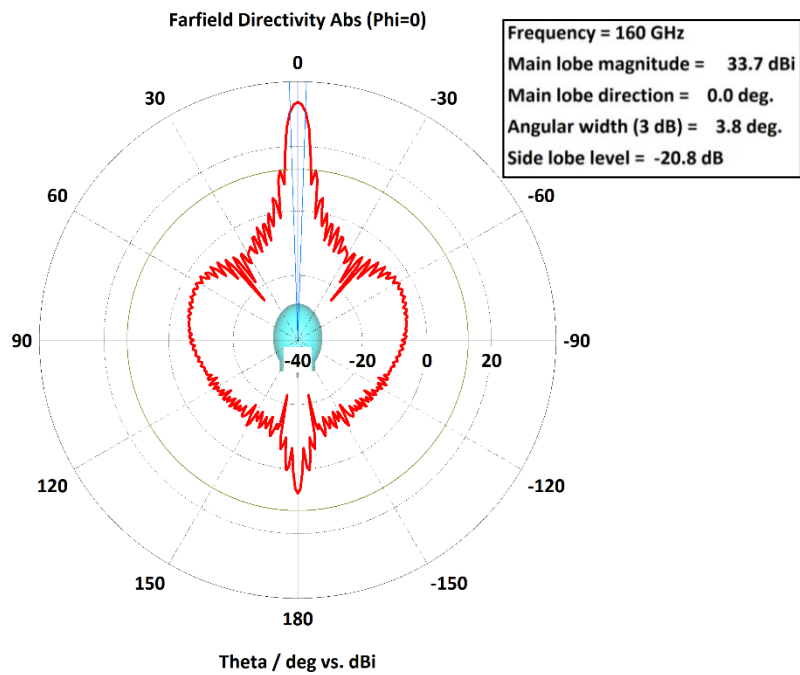


Figure 4.7. 2D Radiation pattern at f=160 GHz.

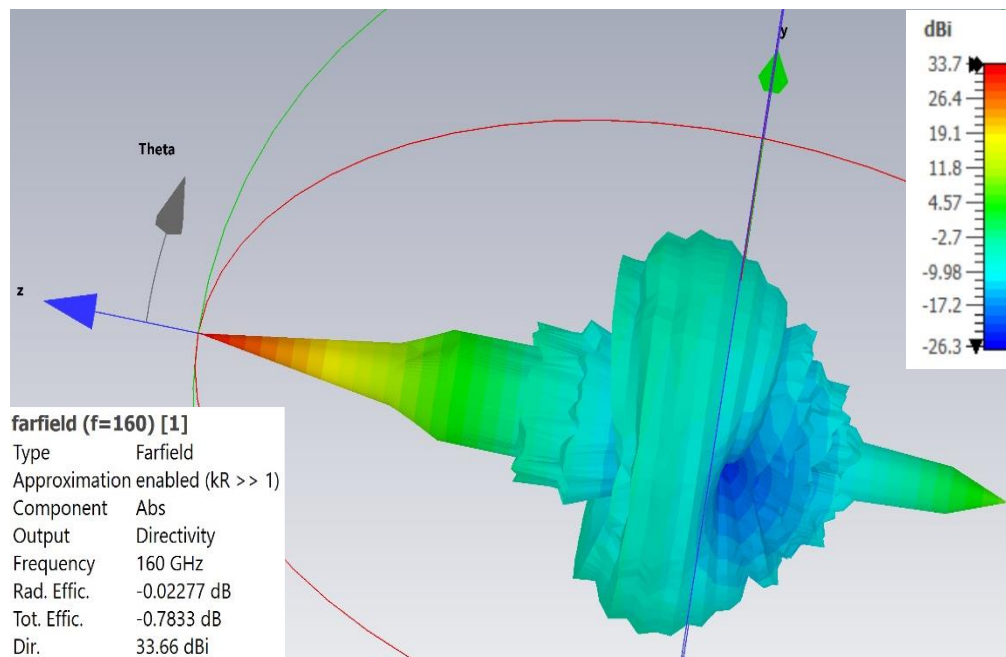


Figure 4.8. 3D Radiation pattern at f=160 GHz.

The results demonstrate that the antenna radiates effectively across a wide frequency band, achieving exceptionally high gain throughout most of the range (144 GHz to 240 GHz) with low sidelobe levels. The maximum gain of 36.3 dB is observed at the central frequency of 240 GHz.

The positive impact of incorporating a lens into the proposed structure is clearly illustrated in Fig. 17. This figure highlights the significant improvement in total gain across different frequency values when the lens is present, compared to its absence.

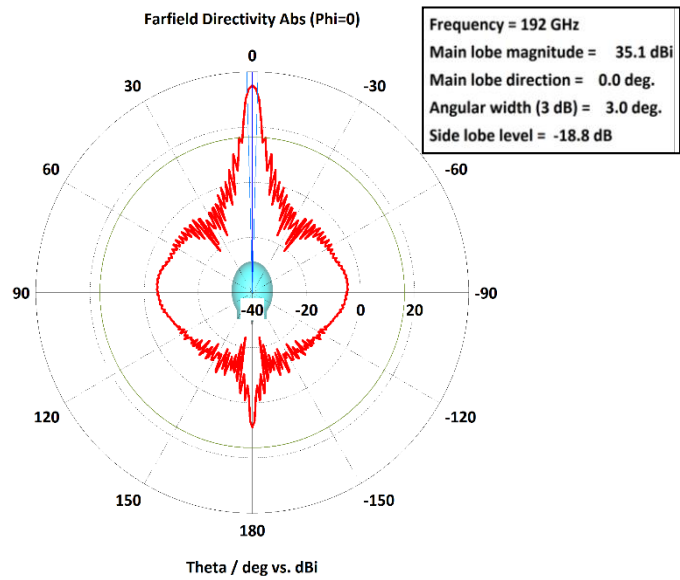


Figure 4.9. 2D Radiation pattern at f=192 GHz.

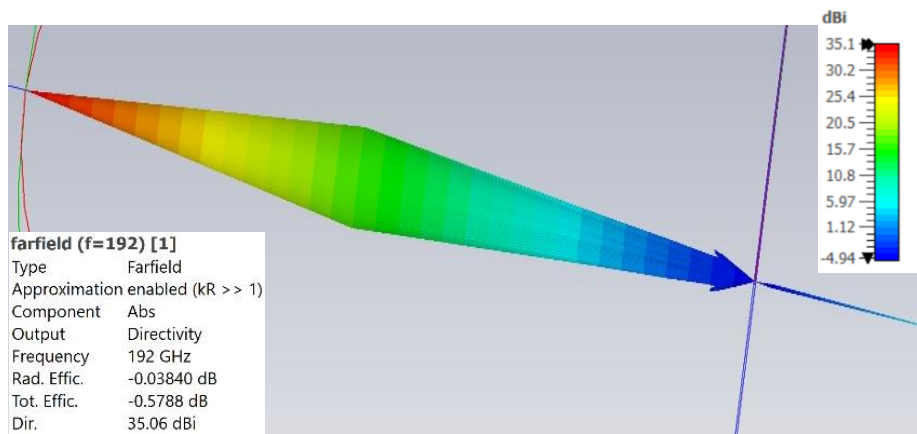


Figure 4.10. 3D Radiation pattern at f=192 GHz.

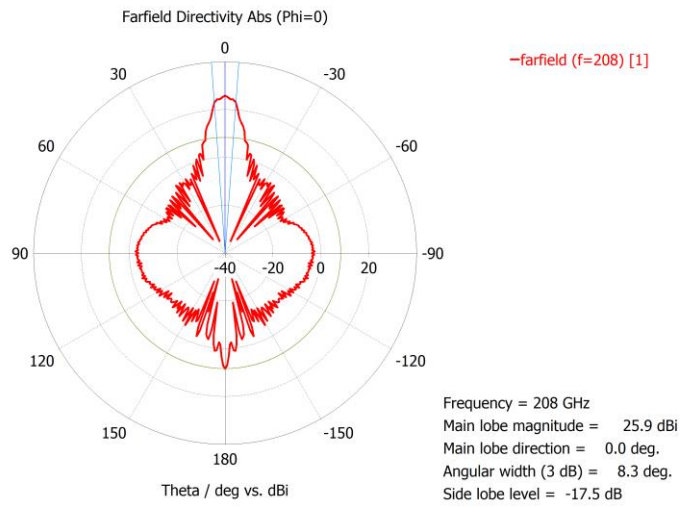


Figure 4.11. 2D Radiation pattern at f=208 GHz.

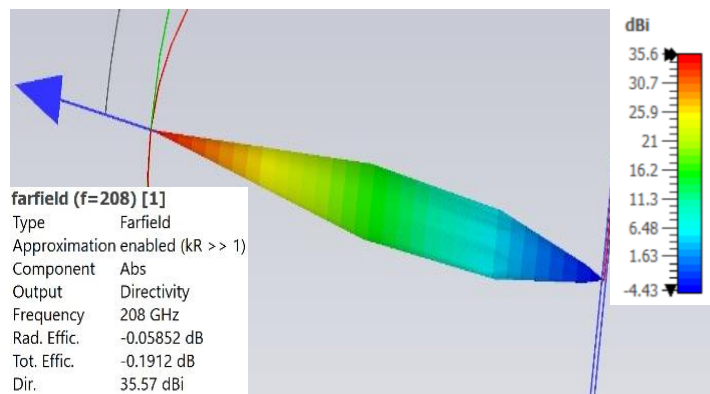


Figure 4.12. 3D Radiation pattern at f=208 GHz.

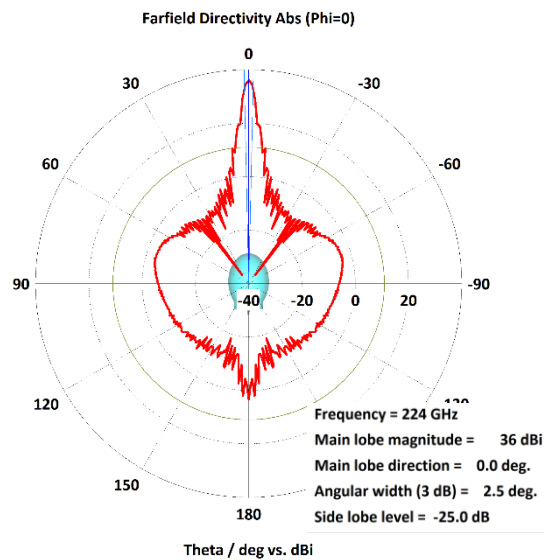


Figure 4.13. 2D Radiation pattern at f=224 GHz.

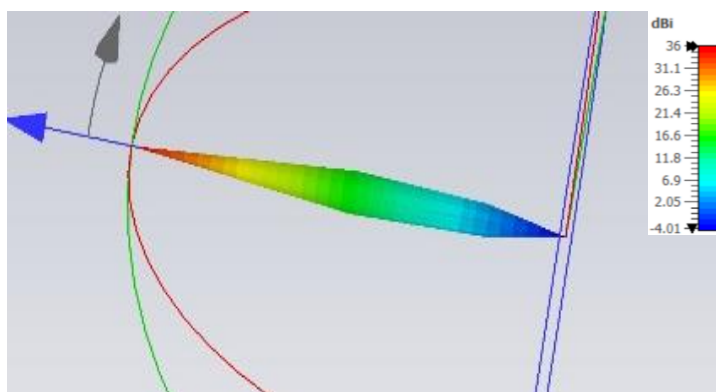


Figure 4.14. 3D Radiation pattern at $f=224$ GHz.

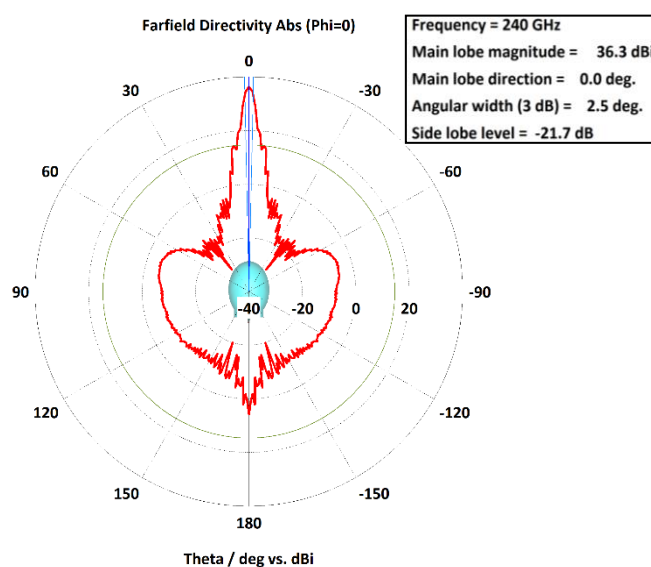


Figure 4.15. 2D Radiation pattern at $f=240$ GHz.

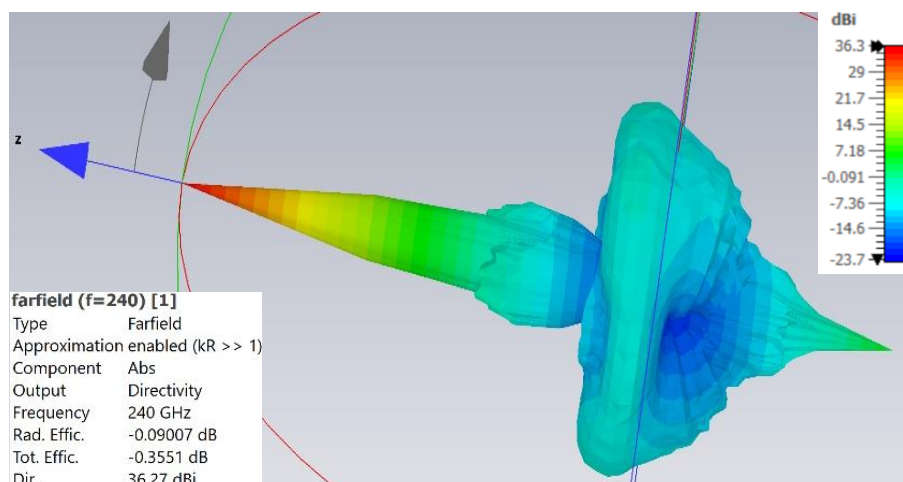


Figure 4.16. 3D Radiation pattern at $f=240$ GHz.

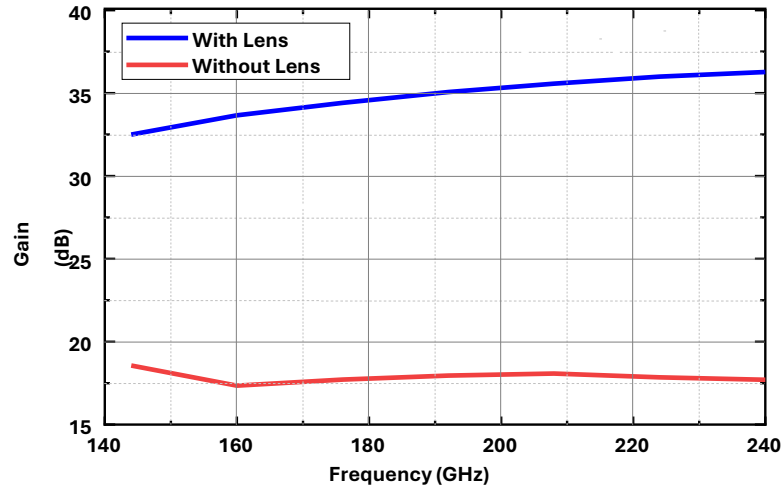


Figure 4.17. Total Gain versus frequency of the proposed antennas.

The Figure 4.17 illustrates the total gain performance of the proposed antenna design as a function of frequency, comparing results with and without the integration of the dielectric lens. The gain values are plotted over a wide frequency range, demonstrating the broadband behavior of the antenna system.

The curve representing the antenna without the lens shows a relatively stable gain of approximately 16 dB across the frequency range. In contrast, the gain curve with the dielectric lens exhibits a significant and consistent enhancement, reaching a peak value of 36.6 dB. This dramatic improvement highlights the effectiveness of the dielectric lens in focusing the electromagnetic waves more efficiently.

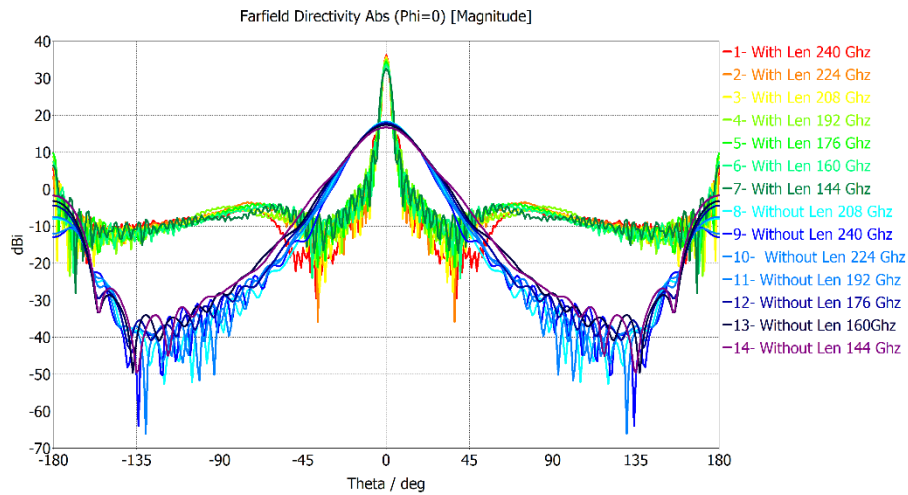


Figure 4.18. 1D Radiation Pattern with and without Lens.

The 1D radiation patterns of the profiled smooth conical horn were evaluated across multiple studied frequencies, revealing significant performance improvements when a dielectric lens was incorporated. The gain increased substantially from 16 dB in the absence of the lens to 36.6 dB with the lens, demonstrating the lens's ability to focus electromagnetic energy into a highly directional beam. This gain enhancement is consistent across the tested frequency range, highlighting the broadband compatibility of the design. The dielectric lens reduces spillover and diffraction losses, which are inherent in traditional horn antennas, thereby concentrating more energy in the desired direction. Furthermore, the radiation patterns exhibit a narrower main lobe and reduced side lobe levels, indicating improved directivity. This is achieved through the lens's ability to reshape the phase front of the radiated waves, ensuring coherent alignment and minimizing energy dispersion. The consistency of these improvements across multiple frequencies underscores the robustness of the design for wideband applications, such as satellite communication, radar systems, and next-generation wireless networks (e.g., 5G and beyond). These results not only validate theoretical models but also demonstrate the practical advantages of integrating dielectric lenses with profiled smooth conical horns to achieve superior gain, directivity, and high broadband performance.

4.4. Conclusion

The integration of the Waveguide-Fed Profiled Smooth Conical Horn and Dielectric Lens Antenna represents a significant advancement in antenna technology for millimeter-wave applications. The combination of the efficient radiation characteristics of the smooth conical horn with the high focusing capability of the dielectric lens achieves remarkable improvements in directivity, aperture efficiency, and radiation pattern quality.

The simulation results demonstrate that the antenna system achieves a peak gain of 36.3 dBi at 240 GHz, with excellent impedance matching and a wide operational bandwidth exceeding 35 %. The hybrid design significantly reduces sidelobe levels and enhances beam symmetry, making it highly effective for demanding applications such as radar systems, satellite communications, and millimeter-wave imaging.

This study underscores the promise of integrating sophisticated antenna geometries and materials to confront the obstacles posed by high-frequency communication systems. Future research could involve further refining the design to achieve additional performance enhancements and investigating its practical implementation in a range of millimeter-wave technologies.

General Conclusion

This thesis presents a comprehensive investigation into advanced antenna technologies, with a particular focus on the design and optimization of dielectric lens antennas. The research sought to address key challenges in achieving high gain, improved directivity, and efficient radiation performance, which are critical for modern communication systems.

The theoretical and experimental analyses conducted throughout this work have underscored the importance of leveraging dielectric materials and innovative geometries to enhance antenna performance. Through extensive simulations using CST software and experimental validation, the proposed designs demonstrated significant improvements in terms of gain, bandwidth, and radiation efficiency compared to conventional solutions.

In the early chapters, we established the foundational principles of antenna design and discussed the role of dielectric lenses in focusing and directing electromagnetic waves. The research further explored the optimization of lens shapes, materials, and integration with feed antennas to achieve the desired performance metrics. The proposed horn antenna-lens assembly exemplified the practical potential of this approach, achieving superior results in terms of directivity and gain.

From a broader perspective, this work contributes to the ongoing advancements in antenna engineering, particularly for applications in mobile networks, satellite communications, and embedded systems. The findings not only validate the effectiveness of dielectric lens antennas but also pave the way for future innovations in the field.

In conclusion, this thesis bridges the gap between theoretical principles and practical implementation of dielectric lens antennas. It provides a robust framework for further research and development in high-performance antenna systems, addressing the ever-growing demands of modern communication technologies. While significant progress has been made, future studies could explore the integration of these designs into emerging technologies, such as 5G and beyond, as well as investigate novel materials and fabrication techniques to further enhance their performance.

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Abstract

This thesis investigates the design of a profiled smooth conical horn antenna integrated with a dielectric lens for sub-THz applications. The research aims to address challenges in high-frequency antenna design, such as propagation losses, and diffraction. A smooth conical horn geometry is developed to enhance radiation efficiency and minimize diffraction. The dielectric lens is incorporated to focus electromagnetic waves, improving gain and directivity. Simulations using CST Studio Suite are employed to model and optimize the antenna, evaluating key performance metrics such as gain, radiation patterns, and efficiency. The combined system demonstrates broadband compatibility and efficient energy concentration, making it suitable for sub-THz communication and radar systems. This work offers a scalable solution for next-generation antenna technologies, providing a foundation for further exploration in advanced high-frequency systems.

Keywords: Waveguide, Profiled, Smooth, Conical Horn, Dielectric, Sub-THz, CST.

ملخص

تتناول هذه الأطروحة تصميم هوائي قمعي ناعم الشكل مع عدسة دييليكتريك للتطبيقات في نطاق تحت التيراهيرتز. الهدف الرئيسي من البحث هو تحسين كفاءة وأداء الهوائيات ذات الترددات العالية من خلال تقليل فقدان الانتشار والتشتت. تم تحسين هوائي القمع الناعم لزيادة تركيز الطاقة وتحسين المطابقة الامتدادية. أما العدسة الدييليكتريكية، فهي تركز الموجات الكهرومغناطيسية مما يزيد من الكسب والتوجيه. تم استخدام برنامج ال س اس تي لإجراء المحاكاة وتقييم وتحسين معايير الهوائي مثل الكسب، والتوجيه، ونمط الإشعاع. يوفر هذا التصميم عرض نطاق واسع وأداء فعال للتطبيقات تحت التيراهيرتز. الهوائي المصمم مناسب لأنظمة الاتصالات والرادار والتقنيات الحديثة الأخرى. وفي الختام، تفتح هذه الأطروحة آفاقاً للبحث المستقبلي لتطوير حلول هوائيات جديدة.

الكلمات المفتاحية: هوائي , عدسة , دييليكتريك , التيراهيرتز , س اس تي.

Résumé

Cette thèse présente la conception d'une antenne à cornet lisse profilé, associée à une lentille diélectrique, pour des applications sous-THz. L'objectif principal est d'améliorer l'efficacité et la directivité des antennes à haute fréquence en réduisant les pertes de propagation et la diffraction. Le cornet lisse profilé est optimisé pour maximiser la concentration d'énergie et améliorer l'impédance. La lentille diélectrique, quant à elle, permet de focaliser les ondes électromagnétiques, augmentant ainsi le gain. Des simulations effectuées avec CST Studio Suite ont permis d'évaluer et d'optimiser les paramètres de l'antenne, tels que le gain, la directivité et le diagramme de rayonnement. Cette conception offre une large bande passante et une performance efficace pour les applications sous-THz. L'antenne développée est adaptée aux systèmes de communication, radar et autres technologies de pointe. Enfin, cette thèse ouvre la voie à de futures recherches pour affiner et développer de nouvelles solutions d'antennes.

Mots-clés : Guide d'ondes, Cornet lisse profilé, Diélectrique, Sous-THz, CST