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Theme

Design Of A Miniature Conformal Antenna For Unmanned Aerial Vehicles UAVs

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Submitted by

- Maria ABDELAZIZ

Supervised by

- Pr.Zahir HAMOUDA
- Mrs.Zeyneb MORDI

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Dedicate

To me, for all the journeys and the ones that are still ahead. May strength and joy accompany me at every step.

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Summary

Antennas are essential components of unmanned aerial vehicles, they handle the necessary wireless communication for critical tasks such as sending and receiving control signals.

This study focuses on the design of a miniature conformal dipole antenna specifically to transmit data telemetry from unmanned aerial vehicles. By altering the physical shape of the antenna, it can adjust its frequency and signal transmission method. The design also aims to be lightweight and compact to suit the strict size and weight constraints of UAVs. The performance of the antenna will be tested using simulations and realization to ensure that it works well and can be easily integrated into drone communication systems.

Keywords: UAVs, Dipole antenna, Miniature conformal antenna, Telemetry data.

المُلَخّص

تُعد الهوائيات مكونات أساسية للطائرات بدون طيار، فهي تُدير الاتصالات اللاسلكية اللازمة للمهام مثل إرسال واستقبال إشارات التحكم.

تركز هذه الدراسة على تصميم هوائي ثنائي القطب مطابق مصغر مُخصص لنقل بيانات القياس عن بُعد من الطائرات بدون طيار. من خلال تغيير الشكل العام للهوائي، يُمكنه تعديل تردده وطريقة إرسال الإشارة. كما يهدف التصميم إلى أن يكون خفيف الوزن وصغير الحجم ليتناسب مع قيود الحجم والوزن الصارمة للطائرات بدون طيار. سيتم اختبار أداء الهوائي باستخدام عمليات المحاكاة والتنفيذ لضمان عمله بكفاءة وسهولة دمجه في أنظمة اتصالات الطائرات بدون طيار.

الكلمات المفتاحية: الطائرات بدون طيار، هوائي ثنائي القطب، هوائي مطابق مصغر، بيانات القياس عن بُعد.

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Abbreviations list

UAVs	Unmanned aerial vehicles
RF	Radio Frequency
MHz	Megahertz
dB	decibel
VSWR	Voltage Standing Wave Ratio
BW	Band width
W	Watt
D	Directivity
LHCP	Left Hand Circulair Polarization
RHCP	Right Hand Circulair Polarization
HF	High Frequency
VHF	Very High Frequency
GNSS	Global Navigation Satellite System
PCBs	Printed Circuit Boards
TCF	Transparent Conductive Film
PET	Polyethylene terephthalate
PTGM	Polyethylene terephthalate glycol-modified
MLS	Meander line antennas
3D	Three Dimensional
CLAS-ACT	Conformal Load bearing Antenna Structure
HFSS	High-Frequency Structure Simulator
ESTA	Ecole des Techniques A´eronautique
FR-4	Flame Retardant

General Introduction

Unmanned Aerial Vehicles increasingly serve critical roles in various sectors such as surveillance, wireless networking, environmental observation, and emergency response. A fundamental element within these systems is the antenna, which must ensure reliable signal transmission while complying with strict limitations on size, mass, and aerodynamic profile. This research focuses on developing mechanical antennas designed specifically for UAV platforms for data telemetry, to enhance communication adaptability without hindering flight performance.

The first chapter of this study begins with a comprehensive overview of antennas with detailing their fundamental parameters, and the diverse array of antenna types is crucial for various applications. In addition, an overview of the categories of unmanned aerial vehicles is presented to contextualize the diverse design and operational requirements on different platforms. Then, the focus is on antenna systems used in UAV platforms, followed by an examination of the essential limitations of conventional antenna designs in such environments.

Chapter Two critically explores advanced solutions based on miniature conformal antennas. The focus is directed towards conformal and miniaturization techniques, which modify antenna properties through physical design changes to optimize performance.

In the last chapter, we will present the antenna structures, made to conform to the curved surfaces of the drone. Using ANSYS HFSS, detailed electromagnetic simulations are performed to optimize the design. Finally, antenna prototypes will be manufactured and will have characteristics.

Chapter 1

State Of The Art

1.1 Introduction

The fundamentals of antennas are presented in this chapter, with a focus on the key performance standards that define their functionality and effectiveness in communication systems. Features such as s-parameter, bandwidth, gain..ect, determine the performance of an antenna.

In addition, there are many different types of antennas, each with unique characteristics designed for a particular application. The chapter also discusses the basic principles of UAVs, conventional antennas used in UAVs, and their limitations.

How do high-performance antennas enhance communication capabilities in unmanned aerial vehicles?

1.2 What are antennas?

A critical element in radio communication, an antenna efficiently emits and captures electromagnetic energy. Typically metal-based, it can also integrate other materials for enhanced functionality.[1]

1.3 Fundamental antenna properties

The first concept to comprehend with respect to antennas is that they are passive devices. They do not require any supply voltage to function. They do not amplify the

RF energy, also they do not alter or process the RF signals. An entirely efficient antenna does not emit more power than the input terminal receives.

An antenna's performance is defined by s-parameters, VSWR (ratio of standing wave voltage), bandwidth, radiation patterns, 3 dB beamwidth, gain, directivity, and polarization. These characteristics significantly influence system functionality.

1.3.1 Scattering parameters

The "S" parameters indicate the reflection and transmission coefficients, well known to RF and microwave engineers. Black-box inputs and outputs they identified by power,voltages, and currents.The "S" parameters resemble the "x" , "y" ,or "z" parameters, which characterize inputs and outputs in relation to signals.

The diagram below elucidates the parameters "S", using the convention where "x" represents an incoming signal to a port and "y" denotes an outgoing signal from a port.

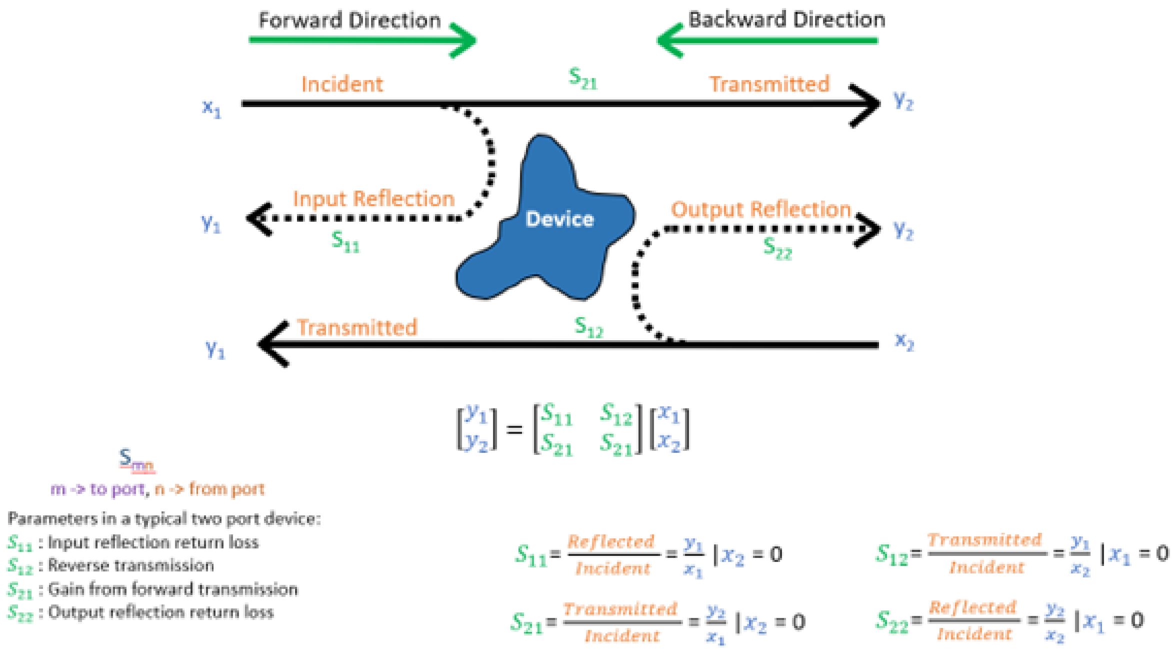


Figure 1.1: S-parameters

Figure 1.1 is referenced from the website article titled "The Complex Art Of Handling S-Parameters ", available at "https://semiengineering.com". [2]

figure 1.1 characterizes the forward and backward directions of signal propagation, defining incident (X_1, X_2) and reflected/transmitted (Y_1, Y_2) waves at each port. Then presented the corresponding matrix equation, which concisely relates the outgoing waves to the incoming waves via the S-parameter matrix. Furthermore, explicit definitions are provided for each S-parameter (S_{11}, S_{12}, S_{21}, S_{22}) in terms of reflected or transmitted power relative to incident power, under conditions of specific port terminations.

1.3.2 Voltage standing wave ratio(VSWR)

The standing wave ratio voltage (VSWR) is a crucial measure of the efficiency of radio frequency power transfer, indicating how much mismatch in impedance from signal reflections affects this efficiency. A lower VSWR value ensures minimal signal reflection and maximum power transmission, while high VSWR values can cause equipment damage, signal distortion, or power loss. VSWR is essential in communication, navigation, radar, and wireless systems for reliable and effective operation.[3]

1.3.3 Working frequency range

The main requirements prove the working bandwidth of the antennas and communication devices, which defines their frequency range. The desired frequency range typically aligns with the operational frequency of the antenna. The term "working bandwidth" describes the extent of this operational range. Generally, omnidirectional antennas can achieve a working bandwidth of approximately 3-5% around their center frequency, while directional antennas can extend this to 5-10%. [4]

1.3.4 Bandwidth

Bandwidth refers to the frequency range that an antenna can operate correctly. It can be expressed as a percentage of the center frequency of the band, with bandwidth being constant relative to frequency.

$$BW = 100 \times \frac{F_H - F_L}{F_C}$$

F_H is the highest frequency, F_L is the lowest,and F_C is the center frequency. Different types of antennas have different bandwidth limitations.

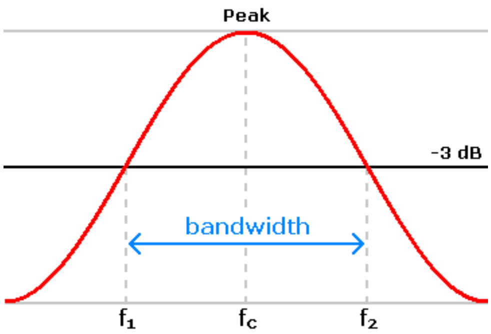


Figure 1.2: Bandwidth

Figure 1.2 provided from the article "Bandwidth of Transmission Medium".[5]

1.3.5 Radiation patterns

A diagram depicts the radiation intensity of a radio or radar antenna that transmits at a specific distance.

The free space radiation pattern, which encompasses all lobes of an antenna, is the complete lobe pattern and is influenced by wavelength, feed system, and reflector characteristics. For a receiving antenna, it responds to a unit field strength signal from all directions. There are two types of radiation patterns: free space radiation, which is the complete lobe pattern, and field radiation, which differs by forming interference lobes when direct and reflected wavetrains interfere.[6]

1.3.6 Impedance

Impedance is a crucial component in both antennas and transmission lines,representing the voltage-to-current ratio along the line. Communication uses transmission lines, typically 50 or 75 ohms, while antennas possess unique characteristic impedances.

The impedance between the antenna and the transmission line must be in the same place to ensure efficient transmission. An impedance mismatch can result in reflections at the interface of the line and antenna, causing less energy storage in the line. Properly designed systems ensure that the impedances of the antenna and transmission line are matched, preventing reflection, and maximizing energy transfer between the circuitry and antenna.[7]

1.3.7 3-dB beamwidth

An antenna's 3-dB beamwidth, or half-power beamwidth, is specified for each principal plane. The angle between the main lobe points, 3 dB below maximum gain, is known as the 3 dB beamwidth in each plane.

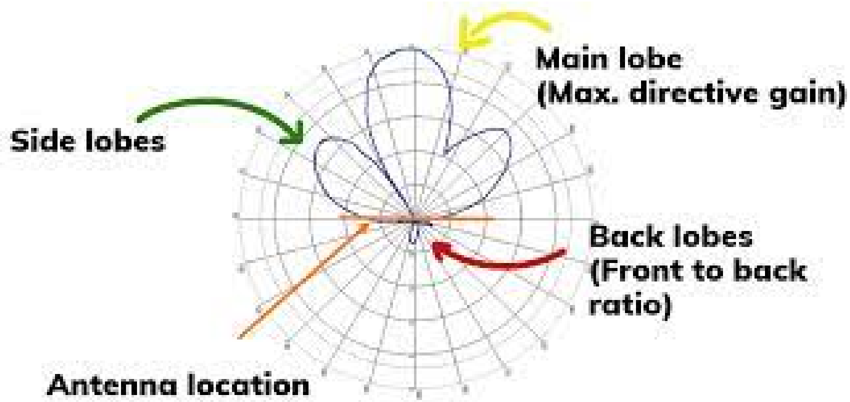


Figure 1.3: 3-dB beamwidth

Figure 1.3 is indicated from the article "How to Interpret Reader Antenna Radiation Patterns". [8]

Figure 1.3 illustrates an antenna radiation pattern, labeling the main lobe (maximum gain) and unwanted side/back lobes. It defines 3-dB beamwidth as the angular separation of the main lobe's half-power points, correlating a narrower beam with higher gain, which is crucial for focused energy transmission or reception.

1.3.8 Gain

Antenna gain is the ratio of the signal output of a system to its input, which is expressed in dBd or dBi. It is a physical measurement of the signal output of a system with its input. A directional antenna with a 13 dB gain requires only 5 W of input power, whereas an optimum unidirectional transmit antenna requires 100 W of input power.[9]

1.3.9 Directivity

Directivity measures how much an antenna focuses its signal in one direction compared to a perfect antenna that spreads its signal evenly in all directions. Measures the antenna's capacity to concentrate energy in a particular direction during transmission or to capture energy from a designated direction during reception.

$$D = \frac{4\pi U}{P_t}$$

Where Pt is the total radiated power in W and U is the intensity of the radiation at the solid angle W / unit.

1.3.10 Polarization

Antenna polarization is the direction of the electric field vector of the electromagnetic wave that an antenna sends out (or receives). It is one of the most basic properties that determines how energy moves through space and how well another antenna can receive it.

Types of Antenna Polarization

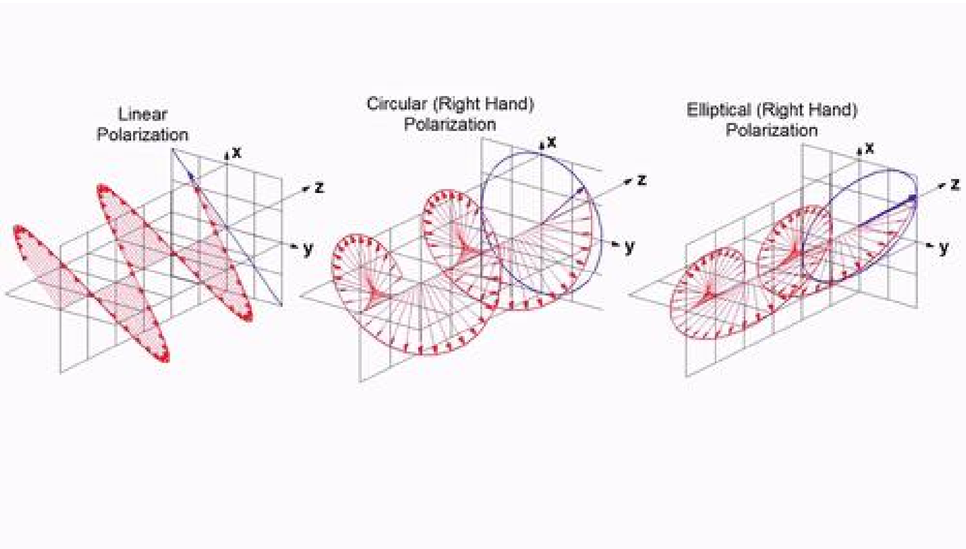


Figure 1.4: Types of Antenna Polarization

Figure 1.4 illustrates the key concept of polarization available at `https://www.times-7.com`".[10]

- Linear polarization refers to the oscillation of an electric field in a single plane, such as vertical, horizontal, or slant. The electric field remains in a single plane during wave propagation, with vertical polarization perpendicular to the Earth's surface, horizontal polarization parallel to the Earth's surface, and slant polarization at an angle to the reference plane.

- Circular polarization occurs when an electric field rotates in a circle as a wave propagates while maintaining a constant magnitude. The electric field vector rotates in a circle perpendicular to the propagation direction, occurring when two orthogonal components are equal in magnitude and 90 ° out of phase. It rotates in right-hand circular polarization (RHCP) or left-hand circular polarization (LHCP).
- Elliptical polarization, the electric field creates an ellipse by combining two perpendicular components with varying amplitude and phase.

1.4 Types of antennas

Antennas can be categorized in various ways, primarily based on their design and function. This classification is essential to choose the right antenna type for specific applications.
Below is an overview of the main antenna types:

1.4.1 Wire-type antennas

Wire antennas, characterized by their conductive wire radiating elements, form a cornerstone of antenna technology due to their simplicity, cost-effectiveness, and adaptability. Their operation depends on the radiation of electromagnetic waves generated by alternating currents flowing through the wire

Dipole antenna

Dipoles are a basic type of antenna. Heinrich Hertz famously used them in his important radio wave experiments. Characterized by its length, which is $\frac{\lambda}{2}$ of its frequency. A dipole antenna typically consists of two metal wires of equal lengthλ, arranged in a two-wire transmission line structure.[1]

Figure 1.5: Dipole antenna

Figure 1.5 is available at `https://www.ahsystems.com`. [11]

Monopole antenna

A monopole antenna is a half-dipole antenna mounted vertically above a conductive ground plane. Image theory explains that the ground plane generates an image current for every real current in the monopole. This configuration reduces the physical size of the antenna based on the quality of the ground plane for proper operation and radiation patterns.[1]

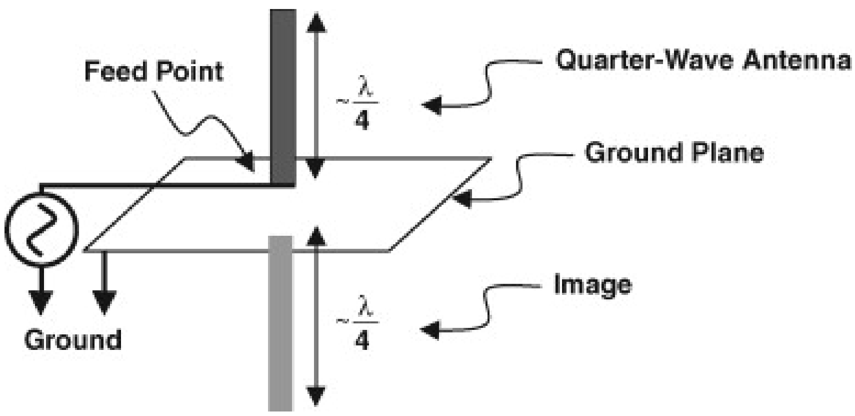


Figure 1.6: Monopole antenna

Figure 1.6 adapted from the book "RFID Handbook by Klaus Finkenzeller. [12]

Loop antenna

A loop antenna is a type of radio antenna formed by a closed loop of conductive material, such as wire or tubing. When an alternating current passes through this loop, it creates a magnetic field that is oriented perpendicular to the loop's surface, enabling the generation and reception of electromagnetic waves for communication purposes.[13]

1.4.2 Aperture antennas

In the fields of electromagnetics and antenna theory, an antenna's aperture refers to a surface located near or on the antenna that allows for convenient assumptions about field values, facilitating the calculation of fields at external locations. Typically, the aperture is considered to be a section of a plane surface close to the antenna, oriented perpendicular to the direction of maximum radiation, through which most of the radiation is emitted.[14]

Horn antennas

A horn antenna is a flared waveguide designed to radiate electromagnetic waves, particularly at microwave and millimeter waves. It provides a wide bandwidth, moderate to high gain, and excellent impedance matching, making it suitable for radar, satellite communication, and compatibility testing.
A dielectric-loaded horn antenna improves its performance by adding a special material inside or close to the opening of the horn. This technique improves gain and bandwidth, enables dual polarization, and ensures strong separation between ports.[15]

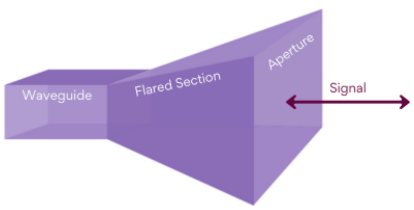


Figure 1.7: Horn antenna

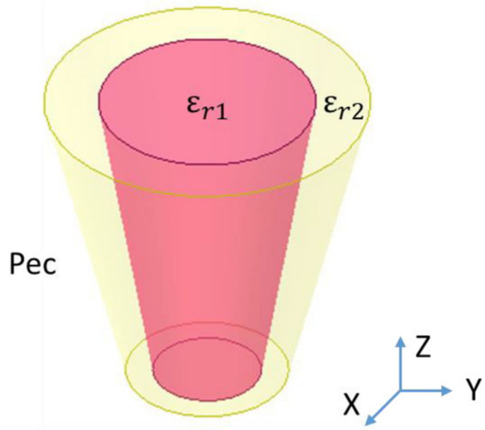


Figure 1.8: Dielectric horn antenna

Figure 1.7 available at `https://www.jemengineering.com`[16]

Figure 1.8 Adapted from the article "Design and simulation of a dielectric-loaded horn antenna using the metamaterial method" by Zhang et al. (2024) [17]

1.4.3 Reflector antennas

Reflector antennas use a reflecting surface to direct electromagnetic waves emitted from a feed antenna. achieving directionality and increased gain.

Parabolic antenna

A parabolic antenna, also known as a dish antenna, is a directional antenna that features a parabolic reflector. It comprises two key components: the parabolic dish and a feed antenna positioned at its center. This design allows for high gain and minimal cross-polarization, enabling the antenna to concentrate radio waves into a narrow beam or to receive signals from a specific direction.[18]

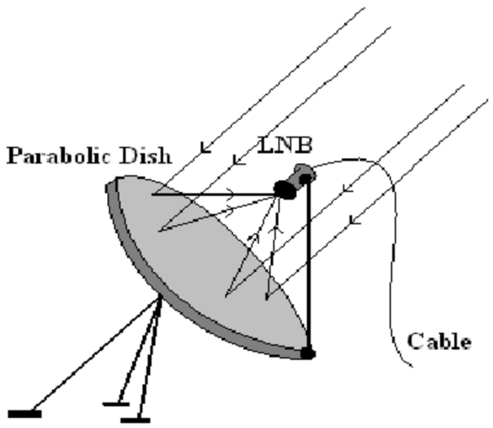


Figure 1.9: Schematic of parabolic reflector dish antenna system

The Figure 1.9 available in the proceedings of the 2013 International Workshop on Antenna Technology (iWAT 2013), IEEE.[19]

1.4.4 Patch antennas

Microstrip or patch antennas are ideal for applications that require low-profile designs while maintaining high performance. Typically, these antennas are made as printed circuit boards (PCBs). Their construction includes a conductive patch and a ground plane, separated by a substrate that may be air or a dielectric material like Teflon. [20]

1.4.5 Reconfigurable antennas

Essential for next-generation communication systems, including 5G/6G networks,cognitive radios,and IoT. Reconfigurable antennas provide flexibility in antenna properties, including frequency, radiation pattern, and polarization. They utilize technologies such as MEMS, PIN diodes, and adjustable materials to adapt to various environments by enhancing bandwidth, efficiency, and reducing interference. Miniaturization,multi-band capability, and artificial intelligence integration have recently gained significant importance.[21]

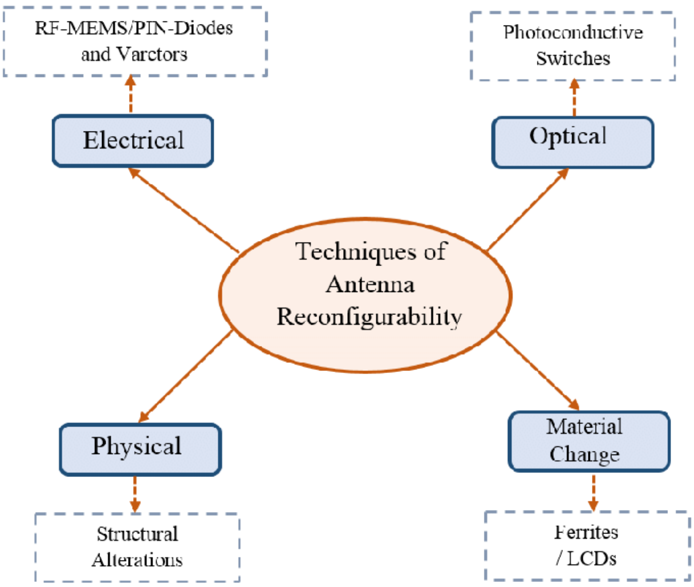


Figure 1.10: Techniques of achieving antenna reconfigurability

Figure 1.10 reproduced from the article "Active Reconfigurable Ultra-Wideband Antenna with Complementary Frequency Notched and Narrowband Response". [22]

1.5 Unmanned aerial vehicles

UAVs are aircraft that fly without a pilot on board. Instead, they're guided remotely either by someone on the ground or through preprogrammed flight paths. Some UAVs fly entirely on their own, others are manually controlled or a combination of both.
Drones (UAVs) often take off and land in ways similar to piloted aircraft. They might be launched with catapults and brought back with parachutes. These drones can operate

from land, ships, or even be deployed from transport aircraft. In terms of design, they usually follow aerodynamic principles more commonly seen in airplanes than in helicopters. Recently, simpler and less traditional designs also become popular.[23]

1.6 Types of UAVs

UAVs come in a range of different shapes and sizes. Typically, it can be classified into four main categories:

1.6.1 A single-rotor UAVs

A single-rotor UAVs (uncrewed aerial vehicle) works much like a helicopter, using a large propeller to lift the ground. Because bigger propellers spin more slowly, they're more efficient and help the battery last longer. These drones can fly forward quickly, hover in place, and carry heavy equipment such as LIDAR scanners. On the downside, they tend to be less stable and cost more because their mechanical parts are more complex.
This complexity also means that maintenance and repairs can be more expensive and time consuming.[24]

Figure 1.11: Single-rotor drones

Figure 1.11 presented in `https://innoflighttechnology.com`[25]

1.6.2 Multi-rotor UAVs

Multi-rotor UAVs are flying machines with two or more rotors that make them super maneuverable, stable, and easy to carry around. Depending on how many rotors they have, they go by different names: tri-rotors with 3 rotors, quadcopters with 4, hexacopters with 6 and octocopters with 8. Their flight time it is usually limited, so for longer missions or larger survey areas.[24]

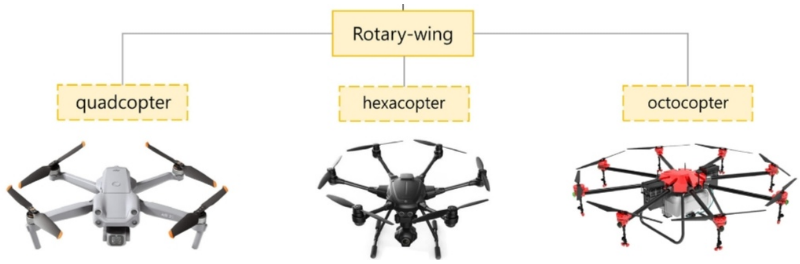


Figure 1.12: Multi-rotor drones

Figure 1.12 Adapted from`https://www.flyeye.io/`[26]

1.6.3 Fixed wing UAVs

Fixed-wing UAVs, similar to traditional airplanes,have a main body and two wings and require a runway or launch device for take-off. They can fly farther because of their low battery power, making them ideal for covering large areas in detail. However, unlike rotor-based drones,fixed-wing UAVs cannot hover or change direction, and they are more expensive to operate. May be needed for safe landings on rough or hard ground.[24]

Figure 1.13: Fixed wing drones

Figure 1.13 sourced from `https://www.uavmodel.com`.[27]

1.6.4 Hybrid UAVs

Hybrid UAVs combine fixed-wing and multirotor systems, allowing vertical take-off and landing, floating, covering large regions and flying for faster and longer periods. These new platforms are suitable for a wide range of applications and are a relatively new platform in the field of glaciology.[24]

Figure 1.14: Hybrid drones

Figure 1.14 presented by Altura UAV on their website `https://alturauav.com/`[28]

1.7 Classification of UAVs

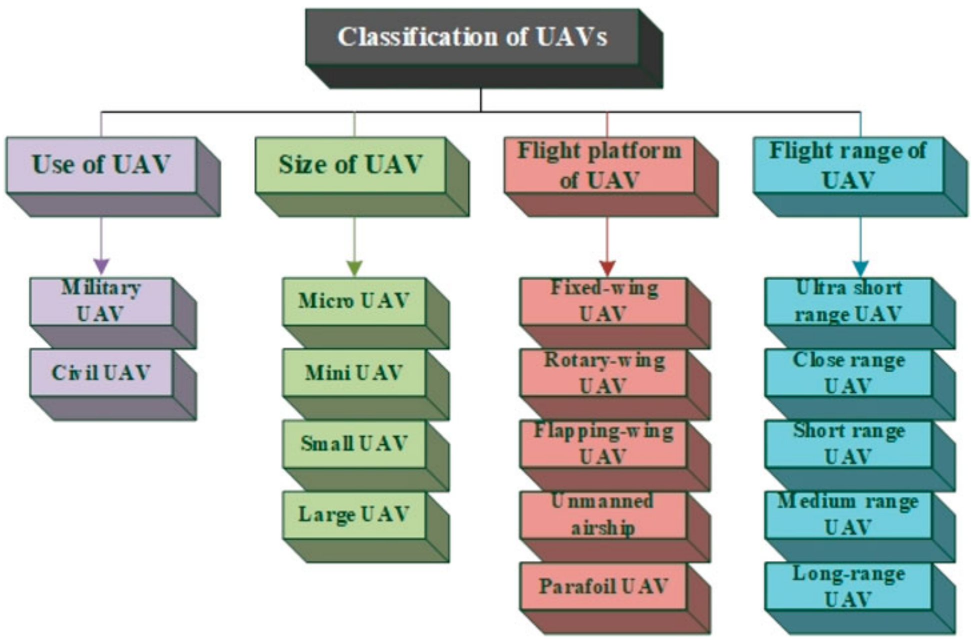


Figure 1.15: Classification of UAVs

1.8 Antennas for UAVs

UAVs use different antennas for communication and operations, which are classified according to polarization (circular and linear).
Special antennas such as GNSS for navigation, telemetry for data, FPV for video, and smart antennas for advanced signal management are also available. Key factors in choosing a UAV antenna include frequency band, gain, radiation pattern, polarization, size, weight, and durability.
Drone antennas are typically used in the L and C bands or the HF, VHF, and UHF bands, with various types available for drone applications.

1.8.1 Types of conventional antennas in UAVs

Although UAVs incorporate various antenna designs, helical, monopole, and dipole antennas are the most frequently adopted.

Monopole antennas:

Commonly used for command.They are omnidirectional but prone to electromagnetic coupling to the fuselage, reducing range and safety. [29]

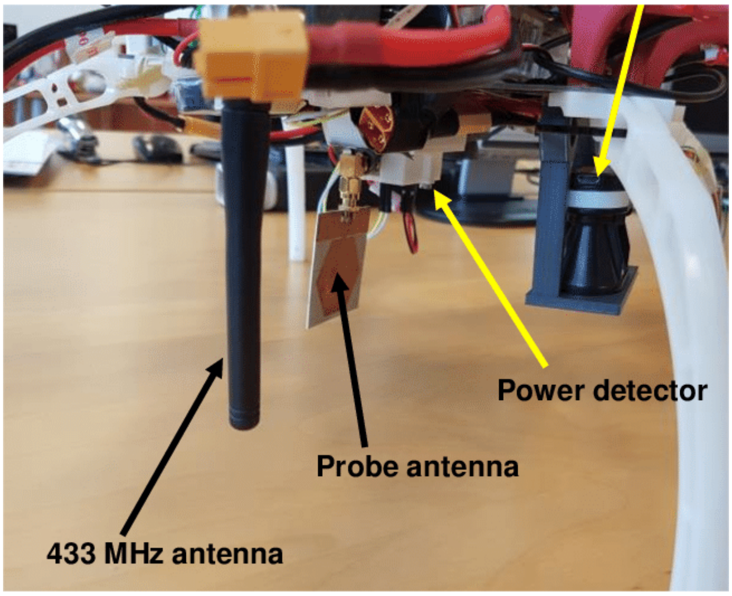


Figure 1.16: Monopole antenna onboard drone

Figure 1.16 from "Antenna Diagnostics and Characterization Using UAVs" [30]

Dipole antennas

Dipole antennas are widely used for control, video, and data telemetry. They are omnidirectional, but they face many obstacles and have limited range in packed RF environments.

Figure 1.17: FPV antenna

Figure 1.17 from `https://avifly.pl/en/`.[31]

Helical Antennas

Essential for navigation and positioning in most types of drones, including hybrids, the most suitable antenna for this application is QHA (quadrifilar helical antenna), but they are sizable.[32]

Yagi-Uda Antennas

Extremely directional, they are used for long-range communication. They need exact alignment and are less suitable for UAVs with often changing orientations.

1.8.2 Limitations of conventional antennas in UAVs

- Size and Weight Constraints: Conventional antennas are often too large and heavy for UAVs, which affects flight performance.

- Aerodynamic drag: Conventional external antennas increase drag, reducing efficiency.
- Interference and signal obstructions.
- Impact damage:the external physical shape of the antenna results in a predisposition to impact damage.

1.9 Conclusion:

The first Chapter outlined the principles of antenna performance, focusing on key parameters crucial for reliable communication. It surveyed various antenna types, elaborating on their specifications and suitability for various applications. In the context of their integration platforms, the chapter also classified UAVs based on their architectural designs and discussed the conventional antenna solutions used.
It was essential to address the critical challenges in the integration of antennas into UAV platforms compared to traditional systems, particularly of specific operational issues. Consequently, these considerations underscore the need for specialized antenna designs that are tailored to the unique constraints and dynamic operational environments of UAVs to ensure optimal communication efficacy.

Chapter 2

Miniature Conformal Antennas

2.1 Introduction

The growing need for flexible and reliable communication systems in unmanned aerial vehicles requires moving away from the limitations of traditional antennas. This chapter will delineate the fundamental principles underpinning miniature conformal antenna technology. Furthermore, it will investigate the innovative methodologies and advanced materials leveraged by engineers and researchers to achieve substantial antenna miniaturization and facilitate their intrinsic integration onto the intricate, non-planar surfaces characteristic of UAV platforms. Ultimately, this discussion will address the significant implications and expansive utility of these highly integrated antenna solutions within the expanding domain of drones.

2.2 Conformal antennas

It is a type of antenna designed to conform to or follow the shape of a curved or irregular surface, such as the fuselage of an aircraft or the body of a vehicle, while maintaining its electromagnetic performance. These antennas are typically composed of arrays of smaller antenna elements integrated on the curved surface, allowing aerodynamic integration and improved spatial coverage without compromising antenna functionality. [33]

2.3 Techniques of conformal antennas

2.3.1 Conformal Mapping Method

It is a powerful mathematical tool for designing antennas on curved surfaces. It works by taking existing antenna designs from a flat plane and accurately transforming them into complex, non-flat shapes like shells or cylinders. This method helps maintain electromagnetic properties while adapting to complex surfaces. [34]

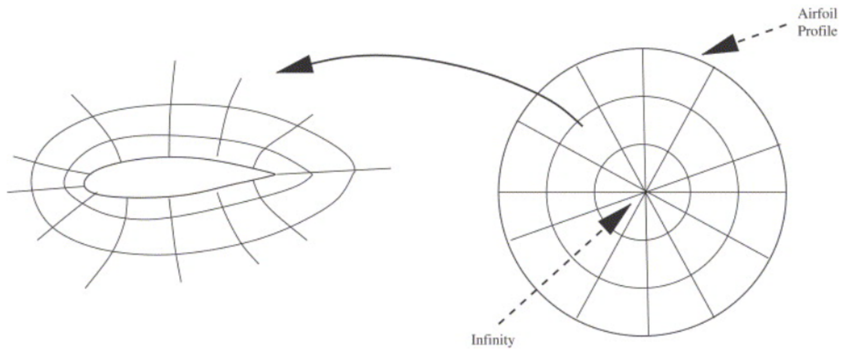


Figure 2.1: Conformal mapping method

Figure 2.1 is adapted from "https://www.sciencedirect.com". [35]

Figure describes the conformal mapping method. It shows how an antenna design from a flat, gridded plane can be mathematically transformed and mapped onto a curved surface, represented by an airfoil profile on a polar grid.

2.3.2 Singly and doubly curved surface designs

Conformal antennas are categorized according to the curvature of the surface on which they are mounted: single-curved and doubly curved antennas.

- Singly curved antennas are mounted on surfaces with a curvature in one dimension, such as cylindrical or conical shapes. Cylindrical conformal antennas are widely used because of their simpler geometry and ease of fabrication. They provide enhanced azimuthal coverage and can achieve omnidirectional radiation patterns. They are commonly applied to missile bodies, aircraft fuselages, and cylindrical vehicle surfaces.[36]

- Doubly curved conformal antennas Doubly curved antennas conform to surfaces with curvature in two dimensions, such as spherical or toroidal shapes. These antennas offer nearly hemispherical coverage, which is advantageous for applications requiring wide angular coverage and aerodynamic integration. Double curvature affects the resonance frequencies and polarization characteristics, necessitating more complex design and optimization. [36]

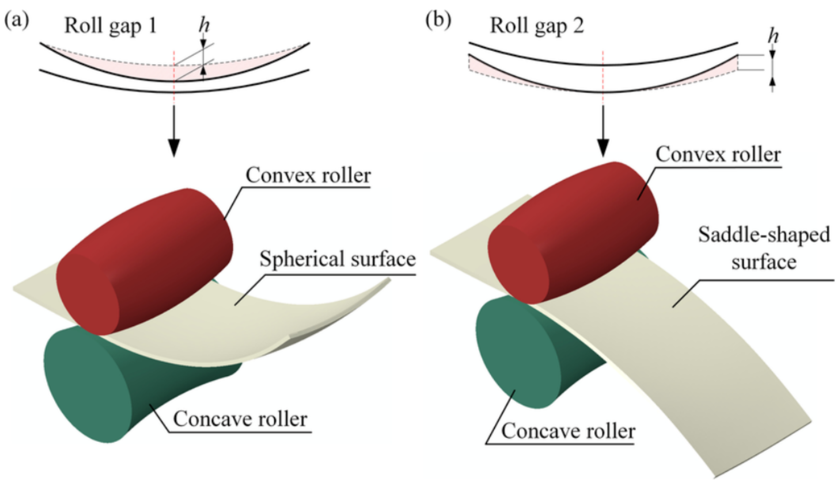


Figure 2.2: Double curved antenna

Figure 2.2 is adapted from the article"The effects of central cross-section diameters of rollers on doubly curved surface rolling". [37]

As shown in the figure 2.2, two methods are illustrated to manufacture doubly curved surfaces, essential for conformal antennas. Specifically, subfigure (a) details the process for generating a spherical surface, while subfigure (b) demonstrates the formation of a saddle-shaped surface, with both techniques employing varied roll gaps between convex and concave rollers.

2.3.3 Microstrip patch antenna design on curved surfaces

Microstrip patches are adapted to curved geometries by adjusting their shapes (quasi-square, rectangular, annular ring, wrap around) and substrate parameters to maintain resonance and polarization characteristics.

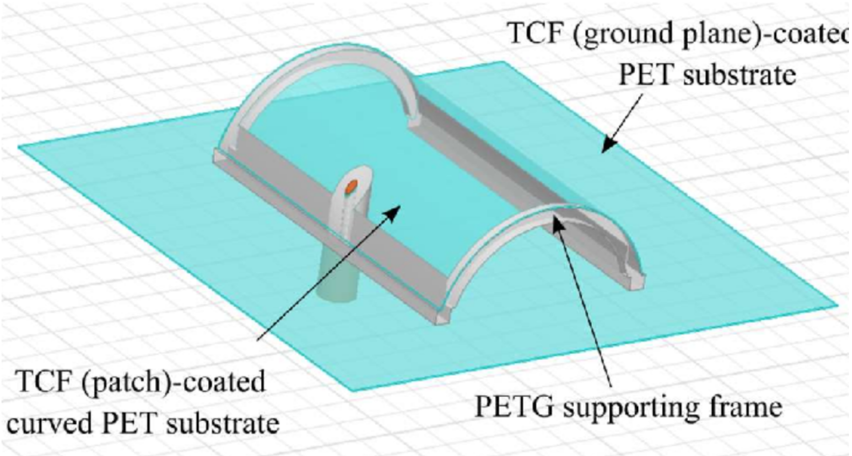


Figure 2.3: Microstrip antenna n curved surface

Figure 2.3 is based on the article "A Curved Microstrip Patch Antenna Designed From Transparent Conductive Films". [38]

Figure 2.3 details a microstrip patch antenna design configured for a curved surface. It emphasizes the integration of a TCF (ground plane)-coated PET substrate with a TCF (patch)-coated curved PET substrate, reinforced by a PETG supporting frame, to preserve antenna performance on a non-planar geometry.

2.3.4 Radiation pattern synthesis and optimization

Techniques such as convex optimization are applied to correct and synthesize radiation patterns in cylindrical or spherical conformal arrays, ensuring desired beamwidth and sidelobe levels.[39]

Figure 2.4 clarifies a methodology to ensure optimal antenna performance in cylindrical topologies. It delineates a radiating patch array in which precise calibration of signal phase and attenuation for individual elements facilitates precise control and optimization of the far-field radiation pattern, thereby reducing the impact of geometric curvature.[39]

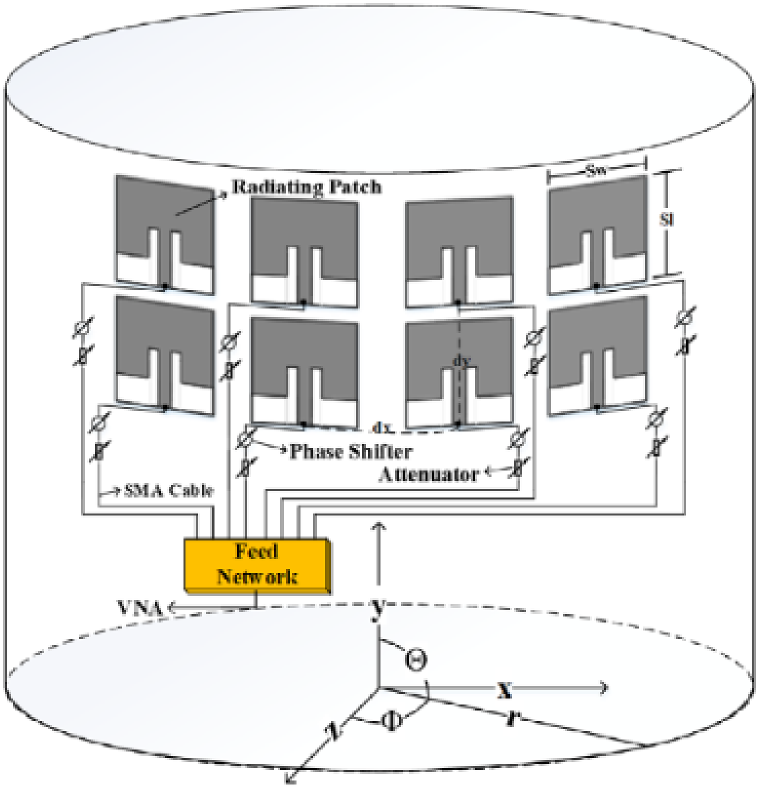


Figure 2.4: Compensation method for cylindrical deformation

2.4 Miniaturization

Antenna miniaturization is technically defined as the process of replicating the original functionality of an antenna while reducing its physical size. Modern advances in design and materials have enabled the miniaturization of antennas without significant performance loss. Miniaturized antennas are especially valuable for applications that require low-profile, lightweight, and easily concealed antennas, such as in intelligence and surveillance. The process involves a combination of mechanical design and electrical engineering expertise to determine feasibility and implement techniques such as slotting, folding, or using advanced substrates to maintain performance despite smaller dimensions.[40]

2.5 Design strategies for miniaturization

2.5.1 Material and Structural Innovations

Topology Optimization

3D conductor-based designs, such as hemispherical copper shells, maximize the current distribution within electrically small volumes. For example, a hemispherical shell with a radius of 79 mm operating at 300 MHz efficiently utilizes the limited space to enhance antenna performance. [41]

Figure 2.5 effectively explains three methods for antenna miniaturization through structural design.

- Size optimization: focuses on reducing the overall dimensions of the antenna while maintaining its fundamental shape.
- Shape optimization: which follows size optimization, this step modifies the specific contours and features of the antenna design.
- Topology optimization: precisely determines where the conductive material (such as copper, or Transparent Conductive Film (TCF)) should be placed within a defined area to form the antenna's radiating structures and ground planes.

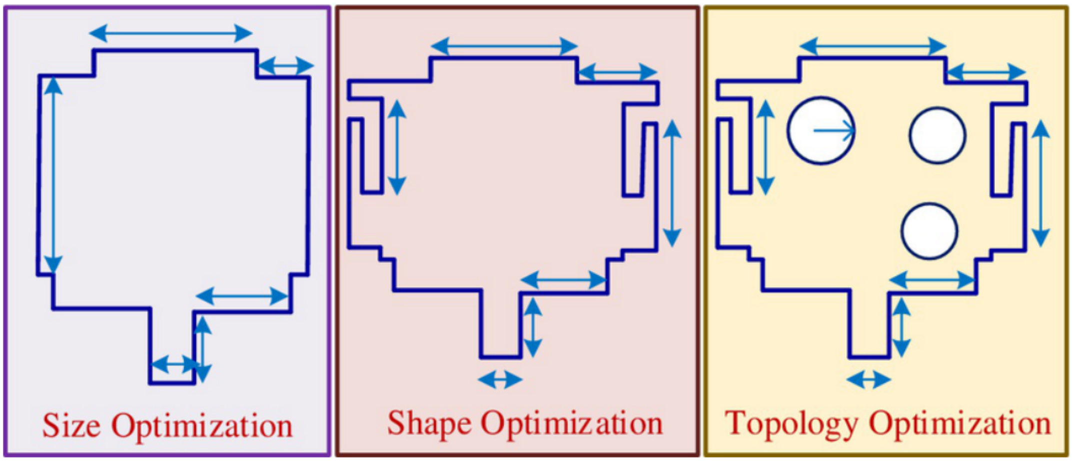


Figure 2.5: Material and structural innovations for antenna miniaturization

Figure 2.5 excerpt from "Overview of Evolutionary Algorithms and Neural Networks for Modern Mobile Communication". [42]

Flexible substrates

Flexible substrates refer to materials that can bend, stretch, or conform to curved surfaces without compromising their electrical or mechanical properties. These substrates enable the fabrication of antennas that can be integrated onto irregular surfaces such as mobile devices, facilitating comfortable and reliable wireless communication. [43]

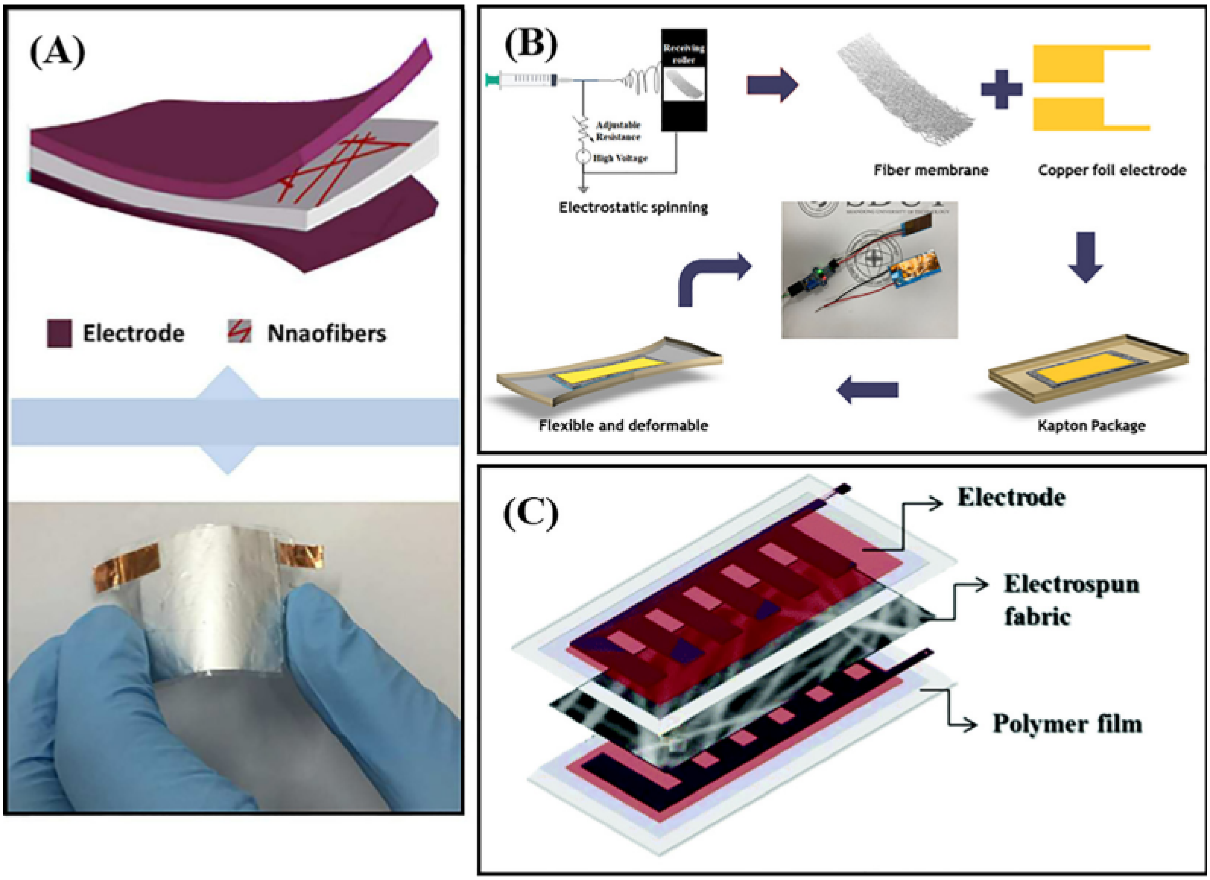


Figure 2.6: Flexible substrates

Figure 2.6 from the article ”Piezoelectric Materials for Flexible and Wearable Electronics: A Review”. [44]

Figure 2.6 illustrates in detail the flexible substrate where :

- (A) Composition of layers of material: demonstrate the fundamental layered structure of flexible substrates for antennas, specifically showing the integration of electrodes and nanofibers, thereby providing insight into their constituent materials. The subsequent step shows the texture of a flexible and deformable structure.
- (B) Fabrication process: electrospinning enables precise fabrication of nanofiber

membranes for integration with copper foil electrodes in energy applications.

2.5.2 Low profile technique

Tightly coupled dipoles

Emphasizing a low profile, compact structure without sacrificing performance. By using a tightly coupled array technique, the physical size of the antenna can be reduced while still maintaining band functionality and omnidirectional radiation characteristics.[45]

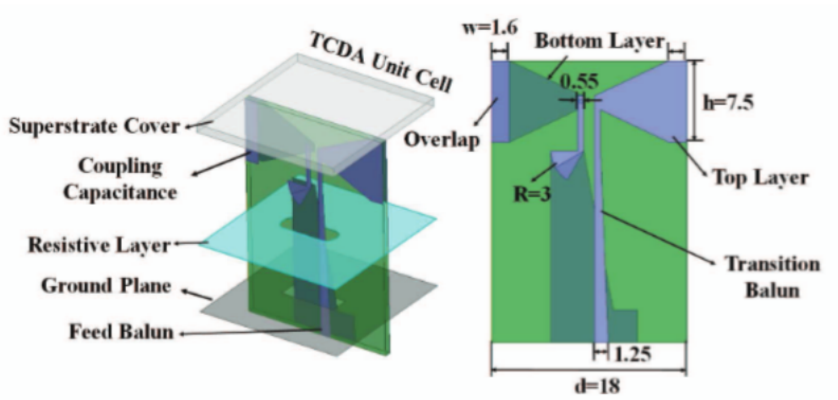


Figure 2.7: Structure of a tightly coupled antenna

Figure 2.7 from the article" Ultrawideband Tightly Coupled Array For Multiband Communications at S-X Frequencies". [46]

Figure 2.7 illustrates a miniaturization technique achieving a low profile antenna through its layered and vertically integrated design, as evidenced by the "TCDA Unit Cell" showing a thin superstrate cover, coupling capacitance, resistive layer, ground plane, and feed balun. This complex stacking minimizes height, which is crucial for compact and integrated applications.

Aerogel Integration

The CLAS-ACT is a lightweight, active phased array conformal antenna constructed from a thin multilayer microwave printed circuit board mounted on a flexible aerogel substrate using innovative bonding techniques.[47]

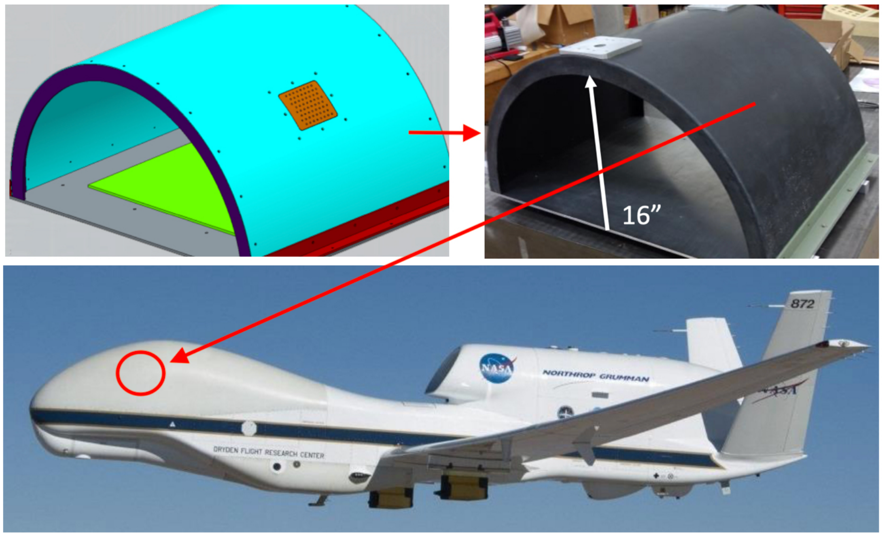


Figure 2.8: Conformal, Lightweight, Aerogel-based antenna

Figure 2.8 is sourced from ”https://technology.nasa.gov”. [47]

2.6 Characteristics of miniature conformal antennas

Miniature conformal antennas exhibit several distinctive characteristics that make them suitable for integration on curved surfaces and space-constrained platforms such as aircraft, UAVs, and satellites:

- A compact size and low profile are fundamental characteristics of miniature conformal antennas, enabling their integration on space-limited platforms while maintaining good radiation performance.[48]

2.7 Examples of miniature conformal antennas

2.7.1 Meander line antennas (MLAs)

These antennas are a type of compact design that use a continuously folded wire structure, made up of alternating vertical and horizontal segments. This arrangement increases the antenna’s electrical length without increasing its physical size, making it especially useful in applications where space is limited.

The operating principle of MLAs is based on their folded structure, which increases the electrical path within the same physical height. This extended path allows the antenna to resonate at much lower frequencies.[49]

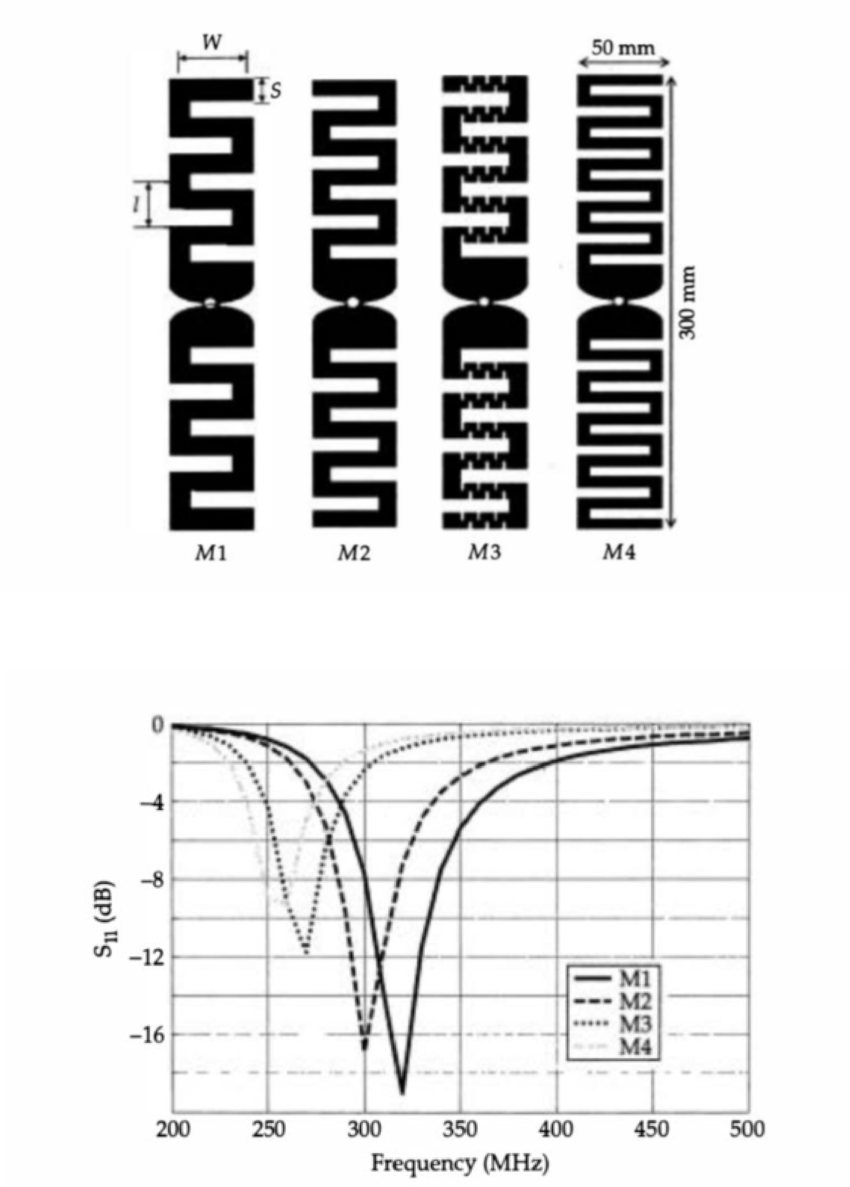


Figure 2.9: Geometry of a meander line antenna

Figure 2.9 demonstrates a miniaturization technique, where increased meandering (M1-M4) within a fixed physical height effectively increases electrical length. This design strategy, as shown by the S11 plot, directly generates a decrease in the antenna resonant frequency. It highlights the inverse relationship between physical compactness via meandering and operating frequency.[49]

2.7.2 A Miniature non-uniform conformal antenna array

A compact non-uniform conformal antenna array designed for UAV applications employs geometric and arithmetic sequences in its element spacing to optimize beam scanning and suppress sidelobes. [50]

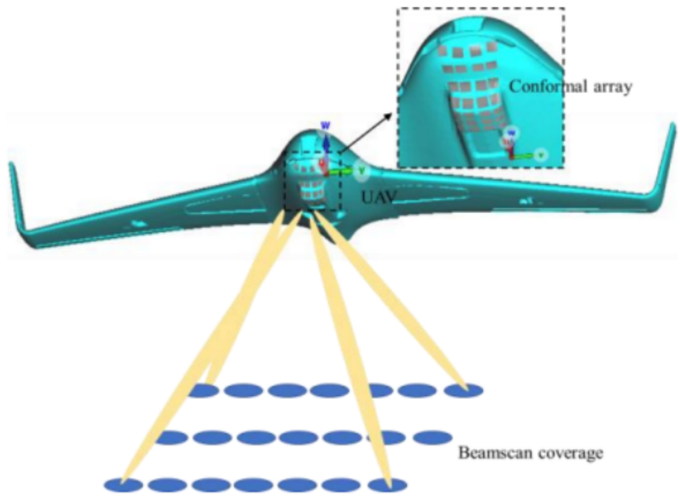


Figure 2.10: A conformal antenna array mounted on a UAV

Figure 2.10 explains a design that employs geometric and arithmetic sequences in its element spacing to optimize beam scanning and suppress sidelobes. This demonstrates an advanced approach to achieving efficient and directive wireless communication from a compact, integrated platform.[50]

2.7.3 Compact wideband monopole antenna

A modified wideband monopole antenna designed specifically for UAV communication,it improves impedance matching and bandwidth performance to support reliable wireless links in drone applications. By optimizing the antenna structure, the design achieves a compact form suitable for integration on UAV platforms, addressing the challenges of limited space and the need for wideband operation in aerial communication systems.[51]

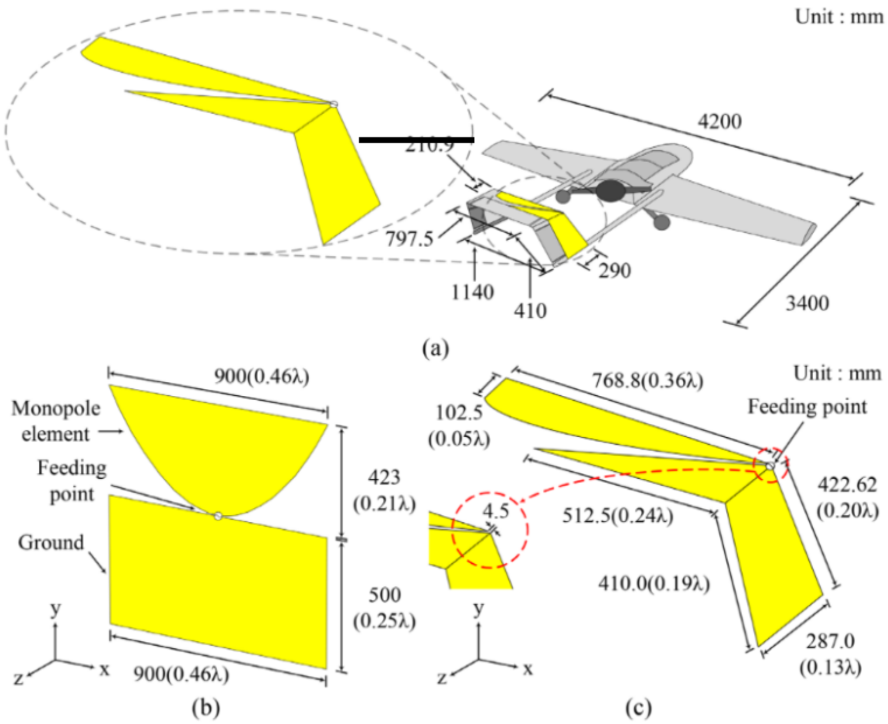


Figure 2.11: monopole antenna tailored for UAV

Figure 2.11 presents the integration of an antenna within a UAV structure. Panel (a) provides an overall perspective of the UAV with the antenna embedded in its wings, illustrating a key application of conformal antenna design. Panels (b) and (c) then delineate the detailed geometry and dimensions of monopole antenna element.[51]

2.8 Feeding techniques for miniature conformal antennas

The feeding mechanisms for miniature conformal antennas significantly influence their performance. The following table details the main feeding types, categorizes them by contact method, and describes their basic feeding principles within the substrate.

Table 2.1: Feeding types for miniature conformal antennas

Feeding Type	Contact Type	Feeding Basics in Substrate
Coaxial Probe Feed	Direct (Contacting)	Inner conductor passes through substrate and connects to patch, outer conductor connected to ground plane. Requires drilling a hole in the substrate.
Microstrip Line Feed	Direct (Contacting)	Conducting strip on substrate edge feeds patch directly, planar structure on same substrate. Simple fabrication.
Aperture Coupled Feed	Indirect (Non-contacting)	Feed line on separate substrate beneath patch, energy coupled through slot (aperture) in ground plane separating substrates.
Proximity Coupled Feed	Indirect (Non-contacting)	Feed line placed on substrate beneath patch, separated by dielectric layer, energy coupled electromagnetically without direct contact.

This table has been derived from both the master's thesis of Redondo González [52] and the study by Shafique et al. [53].

2.9 Performance benefits of miniature conformal antennas for UAVs

- **Enhanced aerodynamics**: Miniature conformal antennas closely follow the curved surfaces of the UAV, minimizing protrusions and reducing aerodynamic drag. This results in better flight efficiency, longer endurance, and better fuel economy.

- **Lightweight and compact design**: The use of advanced flexible materials, such as polymers and aerogels, produces small and lightweight antennas,is essential for UAVs with strict payload and space constraints.
- **Improved communication performance**: Despite their reduced size, these antennas maintain high gain and support wide beam steering, ensuring reliable and adaptable communication links required for diverse UAV missions.

2.10 Conclusion

In summation, this chapter discussed various miniature conformal antenna techniques, which combine compact size with the ability to conform to curved surfaces an ideal solution for space and weight critical applications such as UAVs. These antennas not only help save valuable space but also integrate seamlessly into the platform's structure, enabling improved aerodynamic performance. By combining multiple functionalities into a single low-profile design, they support advanced communication needs without compromising efficiency. Examples presented in this chapter illustrate how miniature conformal antennas can be tailored to fit specific mission requirements while maintaining robust performance. Future work will focus on the detailed design and analysis of a specific miniature conformal antenna optimized for drones platforms.

Chapter 3

Simulation and Realization

3.1 Introduction

This chapter details the design and simulation process of a compact and efficient conformal antenna operating in the 433 MHz band, specifically developed for telemetry applications in hybrid drones. The need for low-profile, aerodynamically integrated antennas necessitates the exploration of conformal designs. The chapter traces the evolution of antenna design, beginning with a fundamental printed dipole concept and advancing toward a miniaturized conformal structure that incorporates strategically placed slots to optimize performance at the target frequency. To ensure precision and effectiveness, the design process extensively utilizes ANSYS HFSS, a powerful electromagnetic simulation tool, to analyze and refine key antenna parameters. This simulation is an operational approach that empowers the development of conformal miniature antennas.
At the end of this chapter, the practical realization and fabrication of the proposed antenna design will be presented, providing a basis for evaluating its potential performance in real-world applications.

3.2 Electromagnetic excitation techniques in HFSS modeling

In this simulation, the utilization of the lumped port enabled the application of defined excitation and the subsequent analysis of the electromagnetic response.

The electromagnetic simulation uses a lumped port to create a basic interface that allows energy to enter or exit a simulated structure. The lumped port functions by treating a specific geometric area as a single electrical terminal which has its own voltage and current characteristics. The abstraction method eliminates the requirement to model the detailed electromagnetic field distribution at the connection point, providing an efficient computational approach to model device circuit interactions.

3.3 Characterizing a copper antenna on an FR4 dielectric

The substrate was modeled using FR4, a common dielectric material in printed circuit board technology, with its relative permittivity ϵ_r and loss tangent $\tan\delta$ defined according to typical values at the operational frequency of 433 MHz. The radiating elements were constructed from copper, characterized by its high electrical conductivity σ, as presented in the following table:

Table 3.1: Simulation property

Component	**Property**	**Value**
Substrate (FR4)	ϵ_r	$\sim 4.4 - 4.8$
Substrate (FR4)	$\tan\delta$	$\sim 0.01 - 0.02$
Dipole (Copper)	σ	$\sim 5.96e7$
Operating Frequency	F_c	433 MHZ

3.4 Design of the initial printed dipole antenna

3.4.1 Antenna geometry

As a foundational step, a printed dipole antenna was designed to resonate approximately around the 433 MHz frequency band. The initial dimensions were calculated on the basis of the half-wavelength principle, considering the influence of the substrate material.

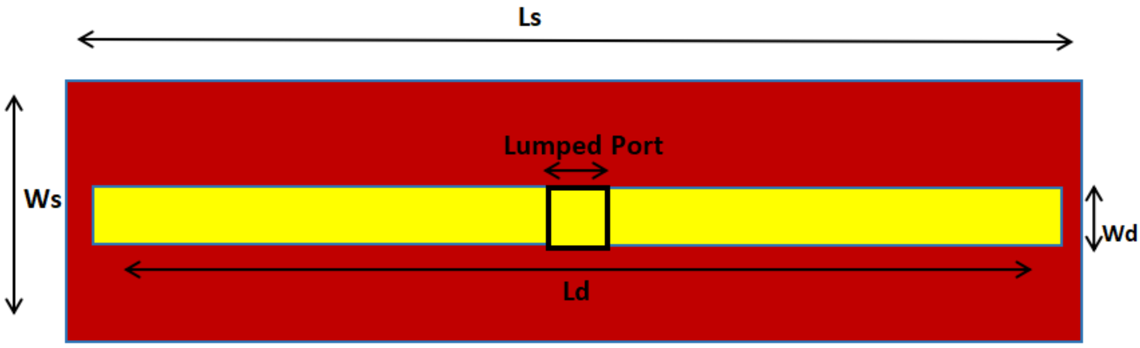


Figure 3.1: Printed antenna

Table 3.2: Dimensions of initial antenna

Component	**Thickness (mm)**	**Width (mm)**	**Length (mm)**
Substrate	1.6	$W_S = 50$	$L_s = 295$
Dipole	0.035	$W_d = 10$	$L_d = 289$
Lumped Port	-	10	11

3.4.2 Simulation setup

The printed dipole antenna designed for the approximate 433 MHz band was simulated using HFSS.

- Boundary Conditions: A perfect electric conductor (PEC) was applied to the antenna elements to represent the conductive material. Radiation boundaries were defined around the structure to simulate the antenna radiating into the free space.

- Excitation: a lumped port.

- Mesh Settings: an appropriate mesh density was applied to ensure the accuracy of the simulation results.

- Frequency Sweep: the simulation was performed over a frequency range encompassing the 433 MHz band.

3.4.3 Simulation results and discussion

- Calculated the theoretical half wavelength:
  $\frac{\lambda}{2} = \frac{c}{2f_0} = \frac{3\times10^8}{2\times433\times10^6} \approx 346.4$ mm
- The simulation results for the antenna determined the effective wavelength to be 289 mm, which is 0.79 λ_0

So, a notable deviation was observed between the theoretical wavelength and the effective simulated wavelength, referring to the theoretical wavelength which assumes an ideal propagation medium. In contrast, the simulated environment incorporates factors such as the dielectric constant of the antenna substrate.

S-parameter

The following figure shows the frequency response of the simulated S parameters:

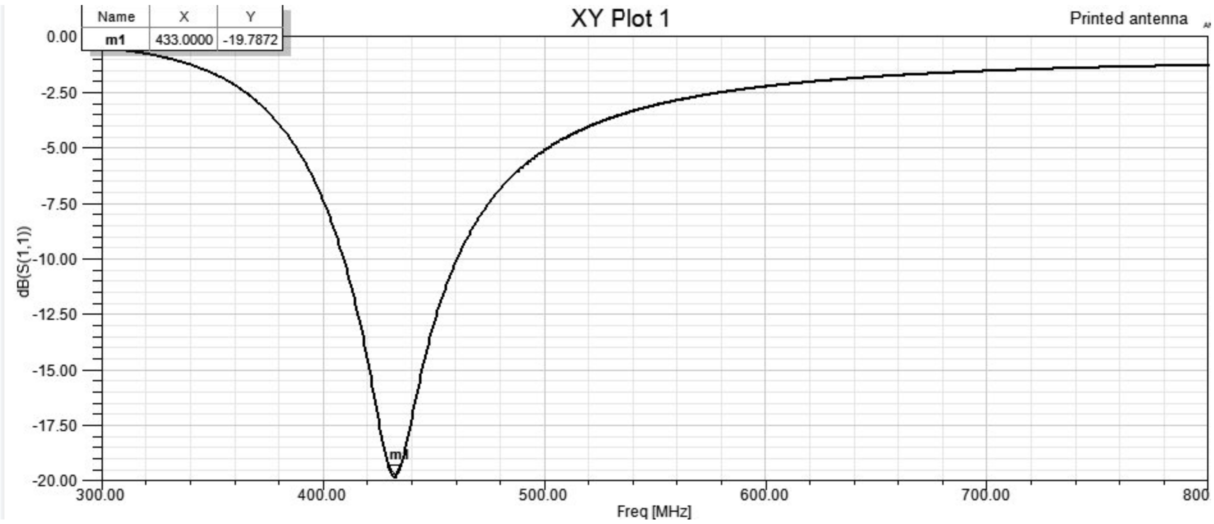


Figure 3.2: S-Parameter

The structure maintains efficient radiation and good matching across the 50 MHz operational band.

Impedance

The resistive component of the antenna input impedance should be close to the characteristic impedance of the transmission line, typically $50\,\Omega$, to ensure maximum power transfer, and the reactive component should be as close to zero as possible.

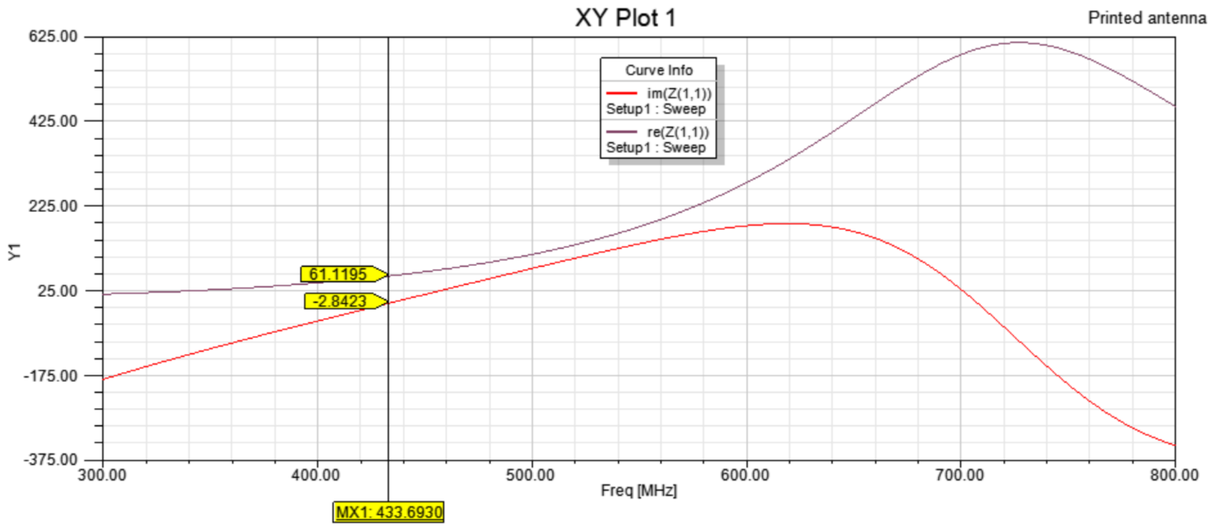


Figure 3.3: Impedance

The input impedance of this antenna is given by

$$Z_{\text{in}} = 61.1 - 2.8j\ \Omega,$$

, which suggests acceptable power transfer with minor reflection losses

Gain

The design achieves a peak gain of 2.34 dB, demonstrating its ability to efficiently direct energy.

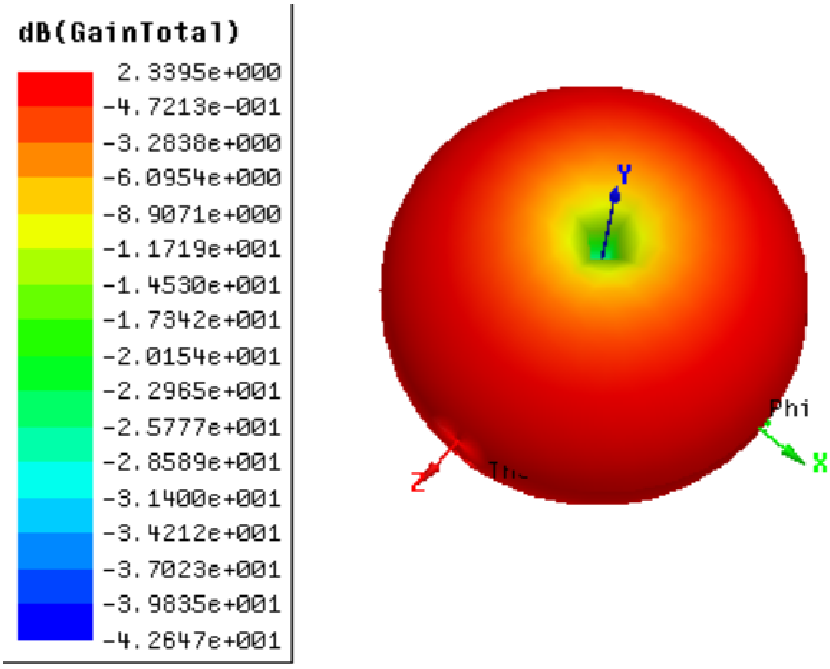


Figure 3.4: Radiation pattern plot (3D)

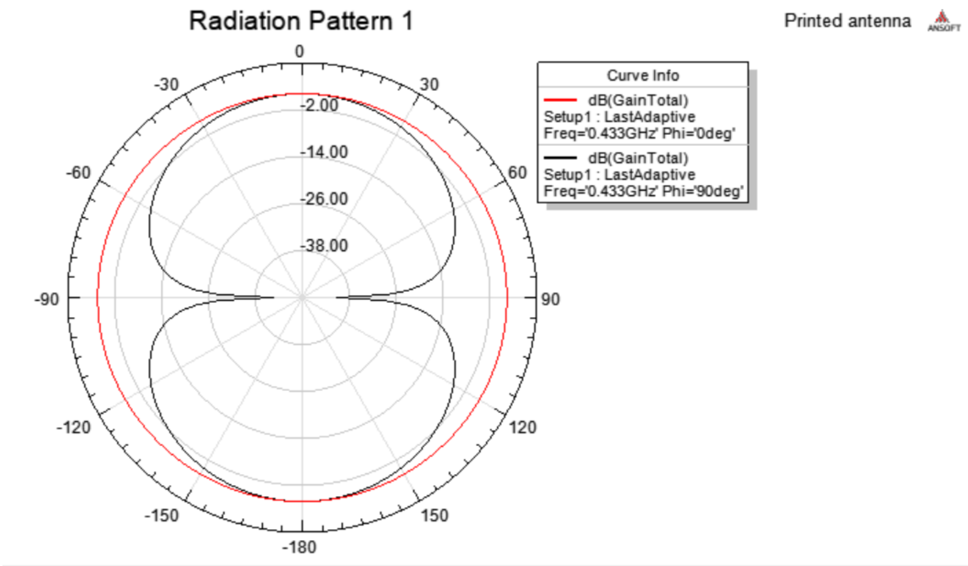


Figure 3.5: Radiation pattern plot (2D)

- This dipole antenna pattern shows good horizontal omnidirectional coverage and excellent signal blocking in specific directions (nulls), as expected.

3.4.4 Synthesising results

These results exhibit favorable performance characteristics. However, despite these positive outcomes, the physical configuration presents limitations for practical integration into hybrid drones, particularly due to its relatively long length and planar design.
Although the antenna performs well, its current form factor is not optimal for direct application in UAV systems without further design modifications aimed at reducing size and improving conformability.

3.5 Design of the conformal antenna

A logical next step in improving antenna design for drone integration involves developing a dipole conformal antenna.
By adopting a conformal configuration, the antenna can better accommodate the curved surfaces typical of UAV structures.

3.5.1 Antenna geometry

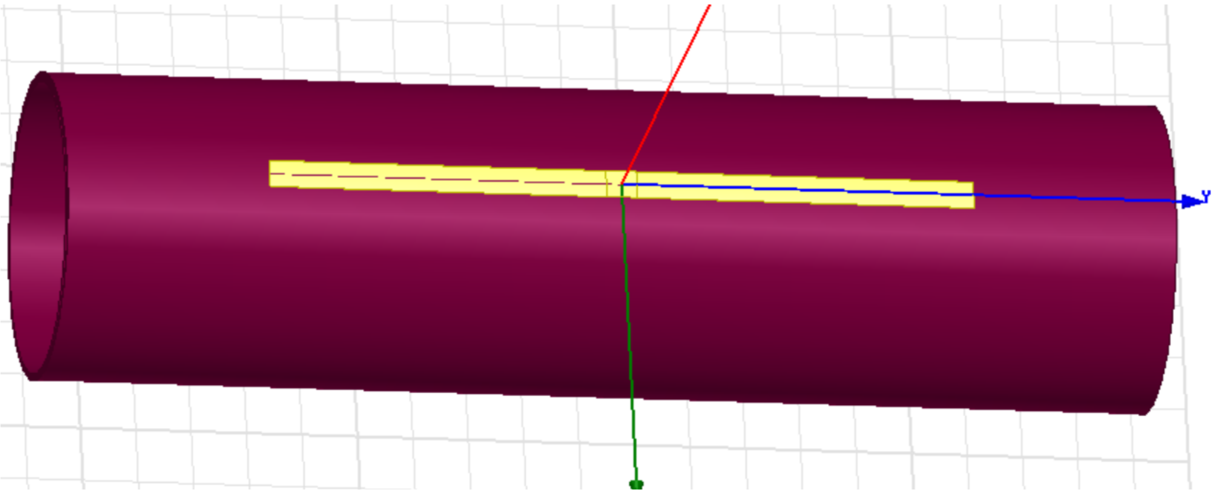


Figure 3.6: Geometric dimensions of conformal antenna

Parameter	Value
Substrate thickness	3 mm
Substrate radius	55 mm
Substrate heught	400 mm
Dipole length	254 mm
Dipole width	10 mm
Dipole thickness	0.0.35 mm

Table 3.3: Conformal design parameters

3.5.2 Simulation results and discussion

Design focuses on a conformal substrate of cylindrical shape. The advantage of this design lies in its ability to adapt to non-planar surfaces, allowing integration with complex structures where traditional antennas would be impractical.

In addition,a physical length reduction from 289 mm to 254 mm a decrease of approximately 12.2%

S-parameter

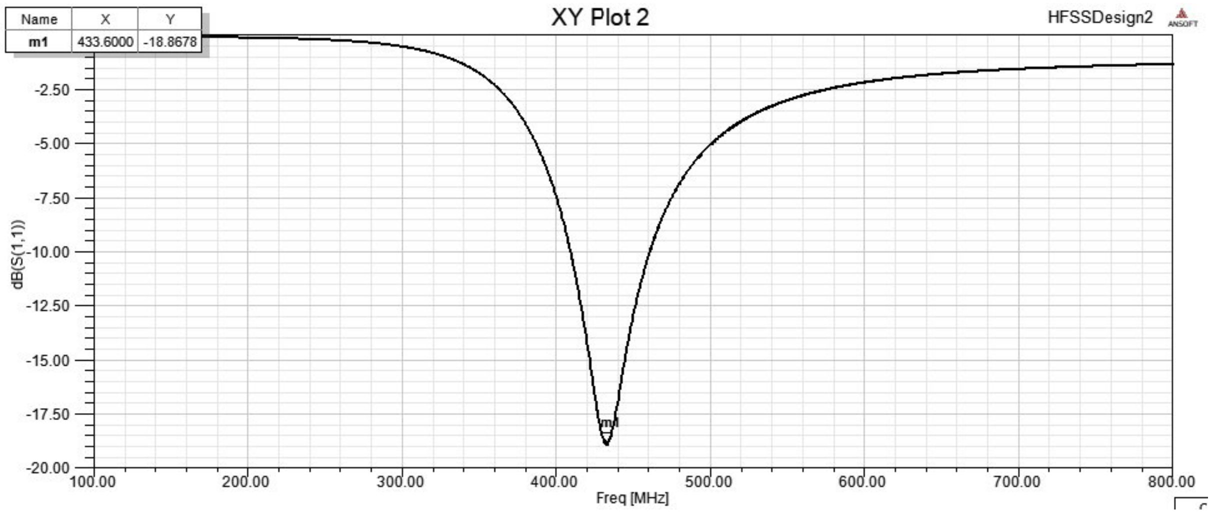


Figure 3.7: S-parameter

The S-parameter data indicates minimal perturbation in the antenna's performance, as compared to the previous design.

Impedance

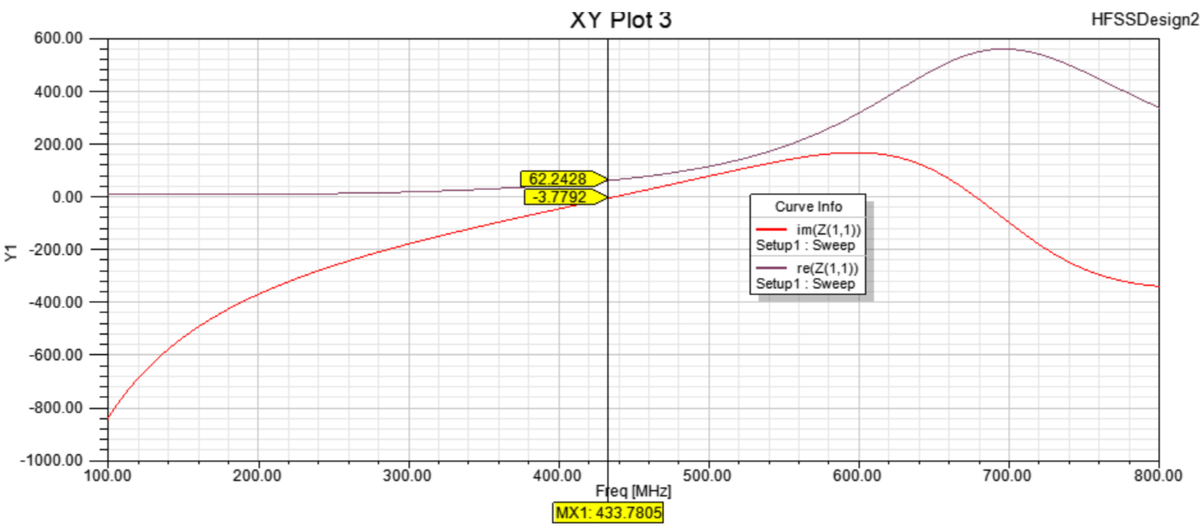


Figure 3.8: Impedance

The input impedance of

$$Z_{\text{in}} = 62.2 - 3.7j\,\Omega,$$

Is somewhat higher than the standard and exhibits a small capacitive reactance, indicating that the antenna is close to resonance but not optimally matched.

Gain

The gain has increased to 2.41 dB, indicating efficient radiation and proper antenna performance.

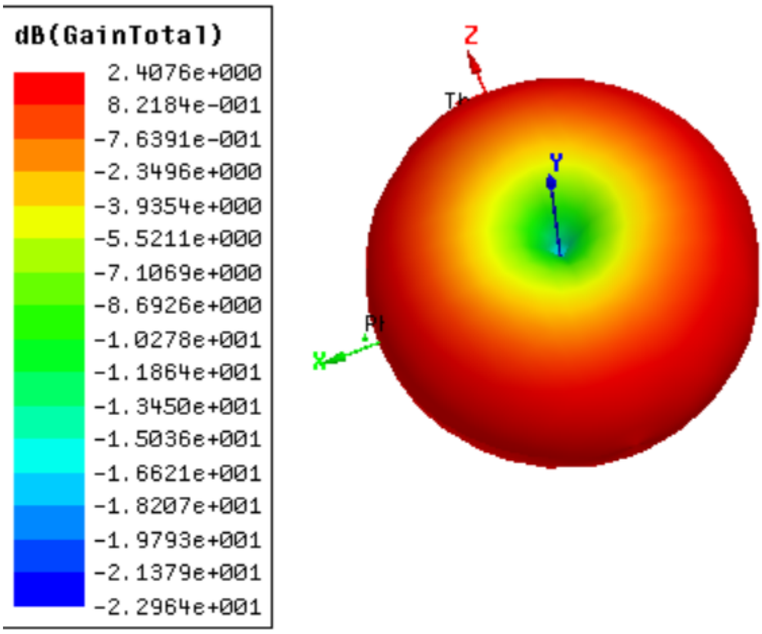


Figure 3.9: Radiation pattern plot (3D)

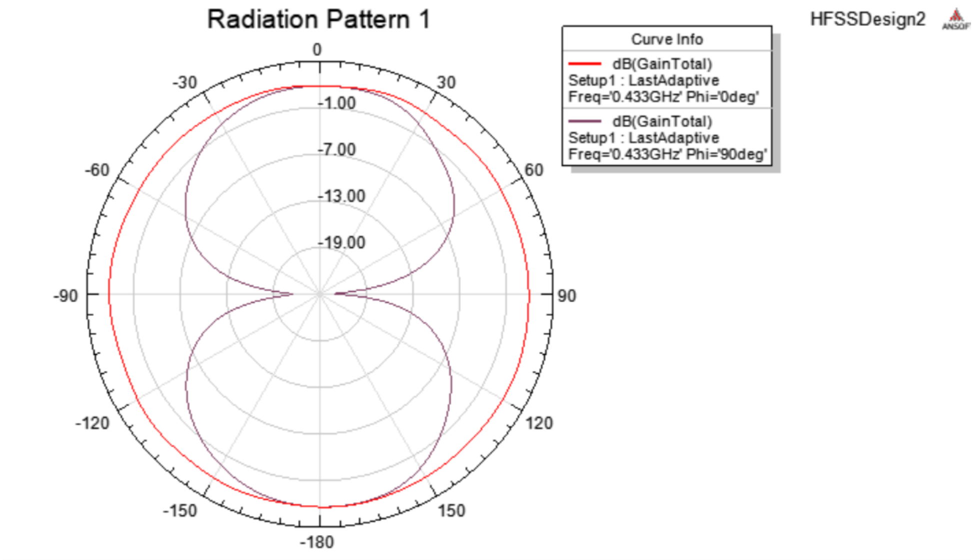


Figure 3.10: Radiation pattern plot (2D)

3.5.3 Synthesising results

The conformal antenna exhibited a slight improvement in gain, although its impedance matching was somewhat less optimal. Therefore, it is evident that further development should focus on this approach to enhance impedance characteristics while maintaining or improving gain performance.

3.6 Design of the miniature conformal antenna

The integration of slots into a conformal antenna structure, as a solution to previously identified performance limitations, fundamentally transforms a static radiating element into a mechanically reconfigurable antenna. This transformation is supported by the principle that physical modifications to the antenna's geometry directly influence its electromagnetic characteristics.
The strategic introduction of slots perturbs the surface current distribution and modifies the effective electrical path lengths across the conformal antenna's radiating elements.

3.6.1 Antenna geometry

This simulation will computationally analyze how changing the slot parameters affects the antenna's electromagnetic response.

Parameter	**Value**
Radius substrate	55 mm
Height substrate	400 mm
Thikness substrate	400 mm

Table 3.4: Dimensions of cylindrical substrate

Parameter	Value
$(L_d/2)$	95 mm
(w_d)	20 mm
(L)	50 mm
Dipole thikness	0.035mm

Table 3.5: Dimensions of the half dipole antenna

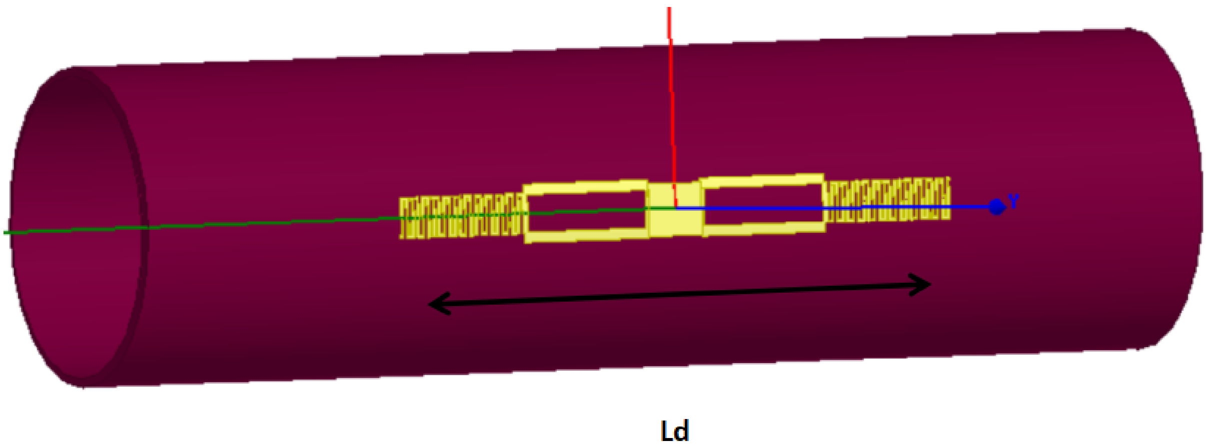


Figure 3.11: Antenna geometry

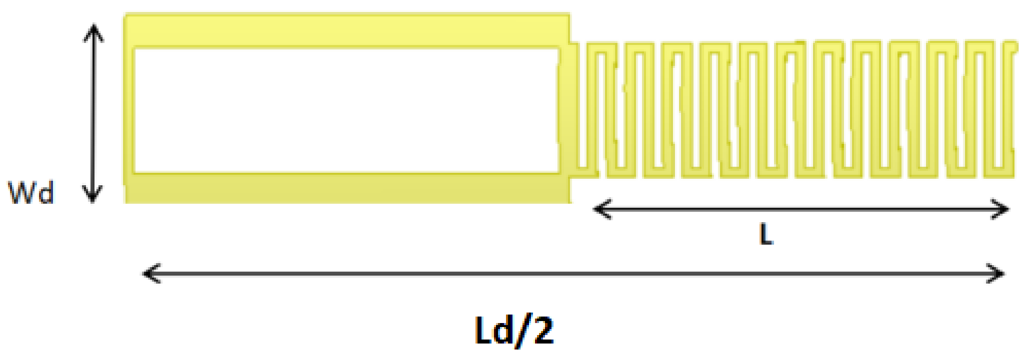


Figure 3.12: Slotted dipole antenna

3.6.2 Simulation results and discussion

- The dipole antenna's length was miniaturized by approximately 48.3%, from 290 mm to 150 mm.

This antenna achieves its excellent characteristics through a strategically optimized geometric configuration and its parameters have been validated.

S-parameter

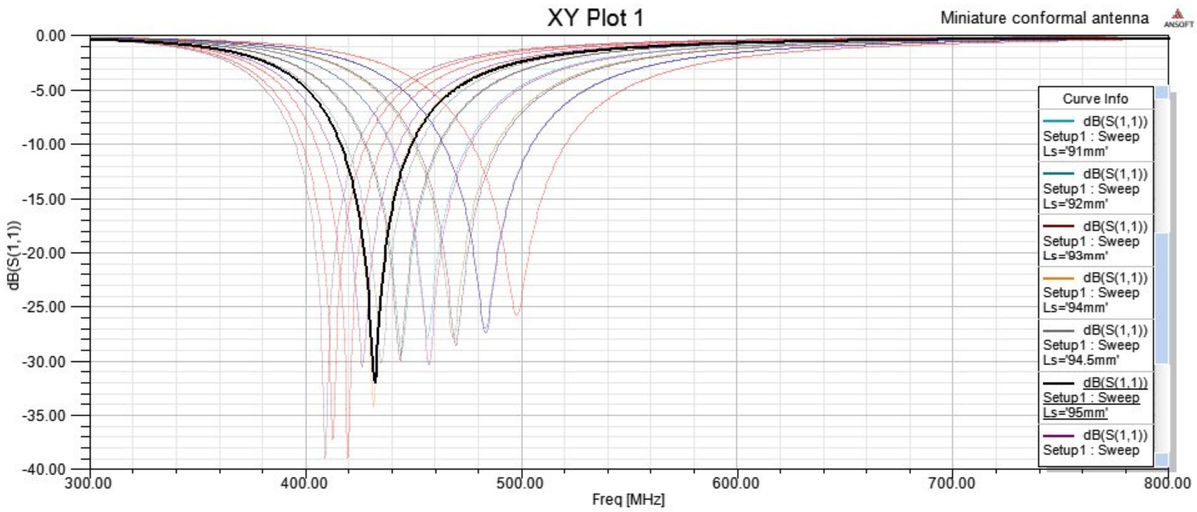


Figure 3.13: S-paramter

The results demonstrate that small dipole antennas can perform excellently when their design parameters are carefully optimized, particularly through S-parameters.

- The following graph represents the antenna size optimized for operation at 433 MHz, ensuring proper resonance and efficient performance at this frequency.

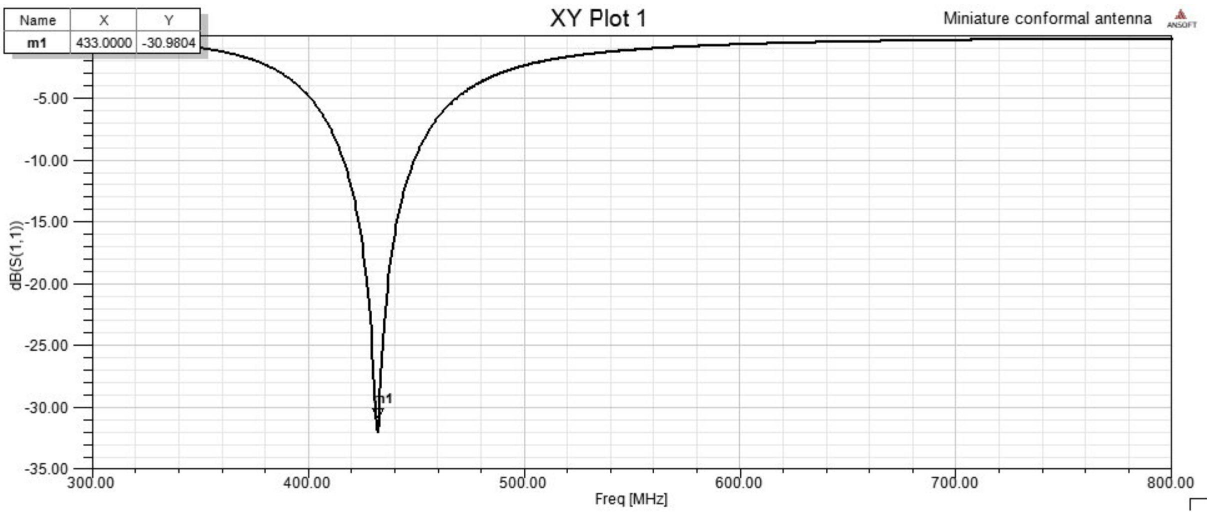


Figure 3.14: Measured S-parameters of the antenna at 433 MHz

- Calculation of reflected power for the S-Parameter : Given an S-parameter value of $S_{11} = -30.9804\,\text{dB}$, the reflection coefficient is calculated as:

$$|S_{11}| = 10^{\frac{S_{11(dB)}}{20}} = 10^{\frac{-30.9804}{20}} = 10^{-1.549} \approx 0.0282W$$

The reflected power ratio is the square of the magnitude of the reflection coefficient:

$$P_{\text{reflected}} = |S_{11}|^2 = (0.0282)^2 \approx 0.0008W$$

Expressed as a percentage, the reflected power is:

$$\%P_{\text{reflected}} = P_{\text{reflected}} \times 100\% \approx 0.08\%$$

This result indicates that only 0.08% of the incident power is reflected, demonstrating excellent impedance matching and efficient power transfer at the antenna input.

Impedance

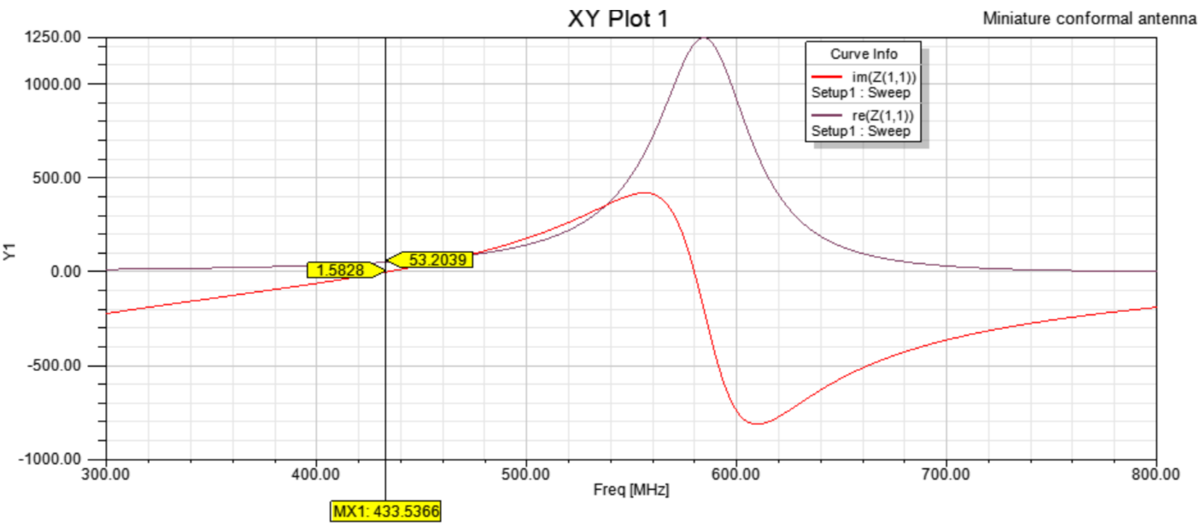


Figure 3.15: Impedance

The input impedance is given by

$$Z_{\text{in}} = 53.2 + 1.5j\,\Omega,$$

This indicates well matched resistively to $50\,\Omega$ a standard transmission line and very close to resonance, with only a tiny, negligible inductive reactance.

VSWR

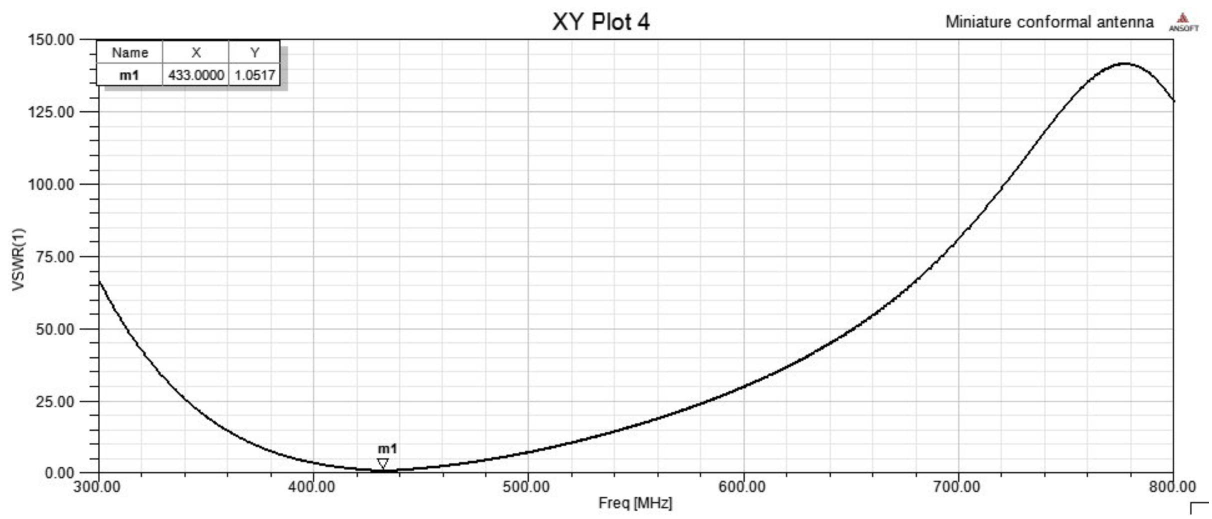


Figure 3.16: VSWR characteristics of the optimized miniature antenna

- The antenna demonstrated an exceptionally low Voltage Standing Wave Ratio (VSWR) of 1.05 at 433 MHz, signifying minimal signal reflection and highly efficient power transfer.

Gain

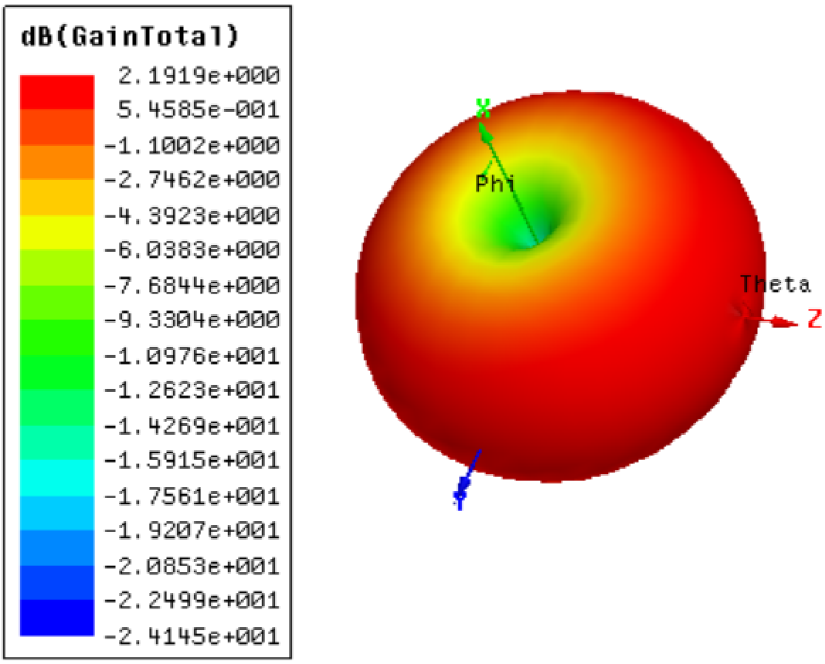


Figure 3.17: Radiation pattern 3D

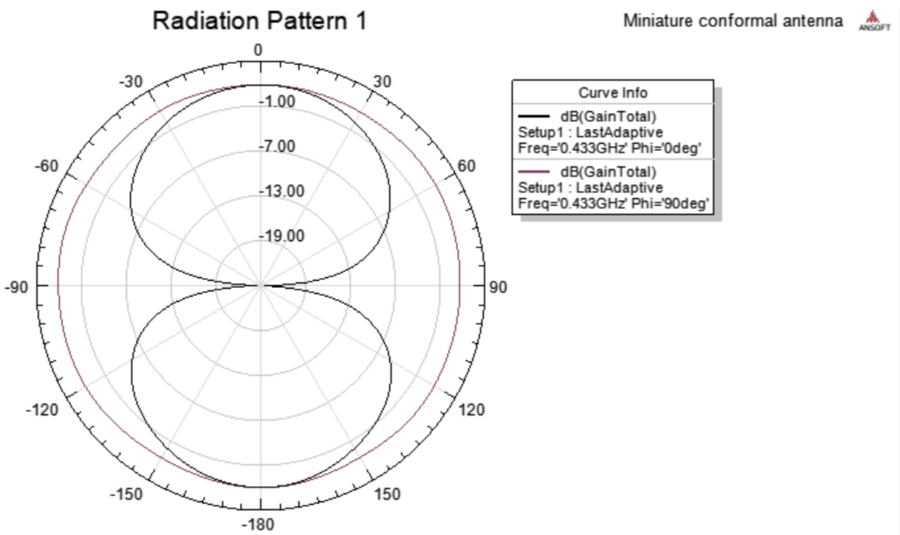


Figure 3.18: Radiation pattern plot (2D)

- Achieving a gain of 2.19 dB demonstrates that the antenna maintains effective radiation efficiency.

Analysis of electric and magnetic fields

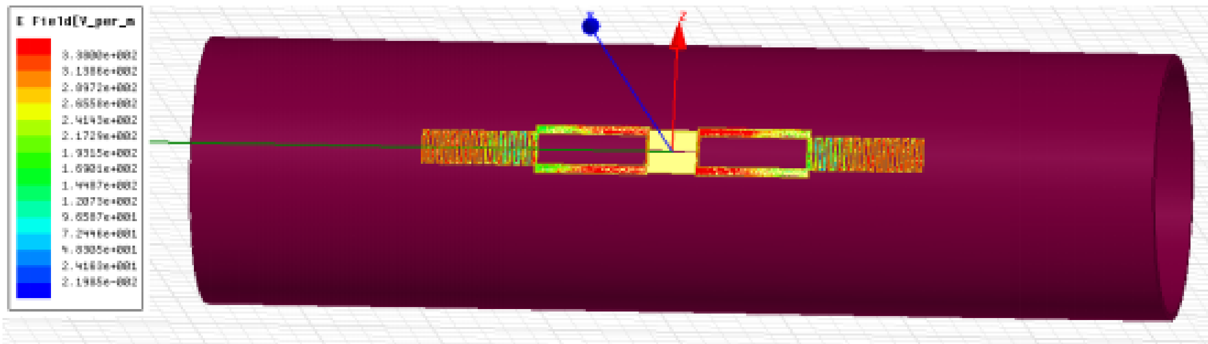


Figure 3.19: E-Field

- E-field: This visualization shows the electric field (E-field) patterns generated by the antenna. The color coding indicates the magnitude of the E field, with red indicating areas of high strength and blue indicating areas of low strength. The presence of strong E-fields is concentrated around the antenna's components.

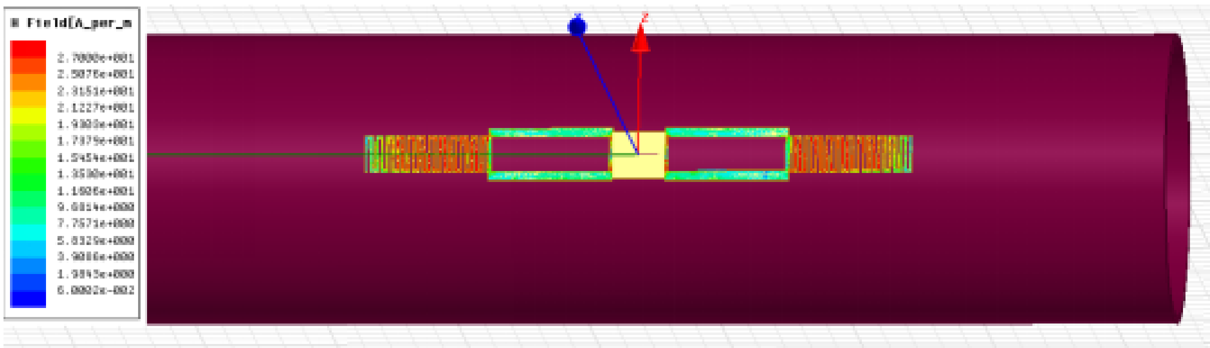


Figure 3.20: H-Field

- The image shows the magnetic field (H-field) intensity across an antenna structure, with the color variations indicating a clear gradient from minimal (dark blue) to maximal (dark red) field strengths, precisely quantifying the magnetic energy distribution. Notably, the highest H-field intensities are localized within and immediately around the antenna's conductive elements, confirming the expected concentration of magnetic energy where currents flow and resonant energy is stored.

Performance evaluation based on electric and magnetic fields

The antenna acts as a transducer, converting electrical energy from the input (oscillating currents and voltages) into mutually coupled E and H fields that detach from the antenna structure and propagate as a self-sustaining electromagnetic wave in free space.

Current density distribution analysis

The "I field," or (J field), describes the magnitude and direction of the the electric current flowing on the surface of the antenna elements at any given point.

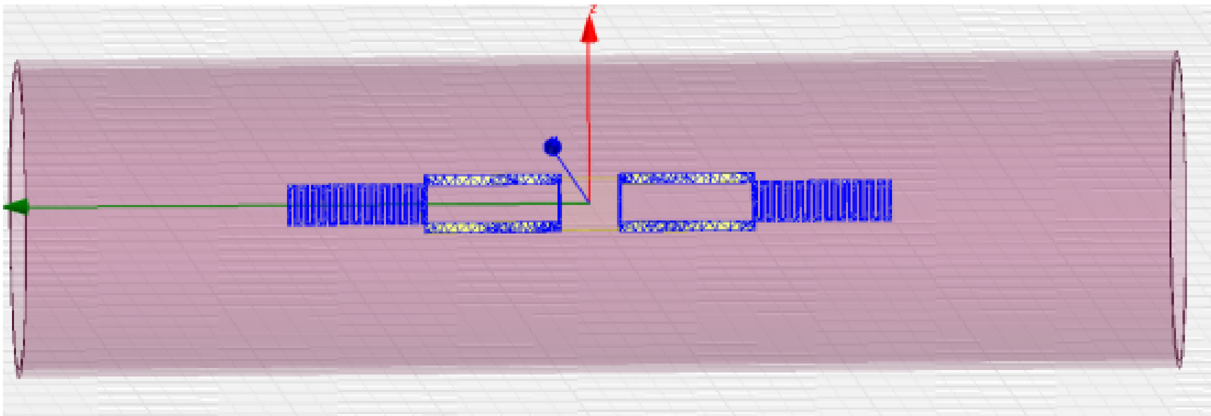


Figure 3.21: I-Field

- Triangle results for the J-field not because the current flows in a triangular pattern, but because the computational grid (mesh) that the simulation uses to approximate the continuous current distribution comprises these small triangular elements.
- J term represents a continuous current density:

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

It's essential to view current as a continuous flow. This isn't just a mathematical shortcut, it is how accurately explain and foresee how electromagnetic waves are created and move.

3.6.3 Synthesising results

By miniaturizing the antenna and adopting a conformal shape, the overall size is significantly reduced while achieving better performance. This design improves the suitability of the antenna for compact, flexible, and curved surface applications.

3.7 Performance comparison

Table 3.6: Comparison of antenna types based on S-Parameter and gain

Antenna Type	**S-Parameter (dB)**	**Gain (dB)**
Printed Antenna	-19	2.34
Conformal Antenna	-18	2.40
Miniature Conformal Antenna	-30	2.19

- The printed antenna measured 294 mm in length. By conversion to a conformal design, the dipole size was reduced to 254 mm, achieving miniaturization 12%. Further size reduction was achieved by adding a space, which decreased the length to 194 mm, representing a reduction of 48%. In general, these modifications resulted in a total size reduction of approximately 60%.

Based on recent simulation and discussion results, the conformal miniature antenna design demonstrates favorable simulated performance, and fabrication will begin to experimentally confirm these properties.

3.8 Realization

The realization of a miniature conformal antenna on an advanced substrate will be presented.

3.8.1 Advanced composite substrate

This work focuses on optimizing epoxy-hardener polymerization processes to develop a specialized fiberglass composite substrate for conformal antenna applications. The resulting fiberglass/epoxy substrate exhibits low dielectric loss and stable permittivity, supporting efficient signal transmission and radiation. Their performance is confirmed through mechanical testing and antenna evaluations, demonstrating their suitability for lightweight and flexible antenna designs.
The following step explains the methodology used to evaluate the suitability of the developed substrate:

- Material Preparation: The preparation started with choosing a PVC tube as the base material mold. We achieved a uniform texture by sandpapering the exterior of the pipe. The tube was smoothed because it removed both imperfections and contaminants.

- Mold Preparation: The next step was to apply a release agent which functioned as a thin protective coating to keep the substrate away from the pipe. The main purpose of this process was to prevent the component from flowing and sticking to the tool surface during stratification, so that it could be easily removed. Then, parchment paper was placed on top of the mold surface to create an extra non-stick coating. This procedure reduced the possibility of damage to both the PVC cylindrical section and the substrate.

- The preparation involved the shaping operation using fiberglass with gram mage 160 g/m^2. The material was applied in ten layers, with each ply measuring 35 × 55 mm in rectangular format. The layered application method produced the required form and structural properties. Fabrication required the sequential addition of plies with a mixture of 77% epoxy resin to 23% hardener between each layer to create strong bonds between the fiberglass layers, resulting in a solid structure. Then it was formed within the confines of the tubular mold.

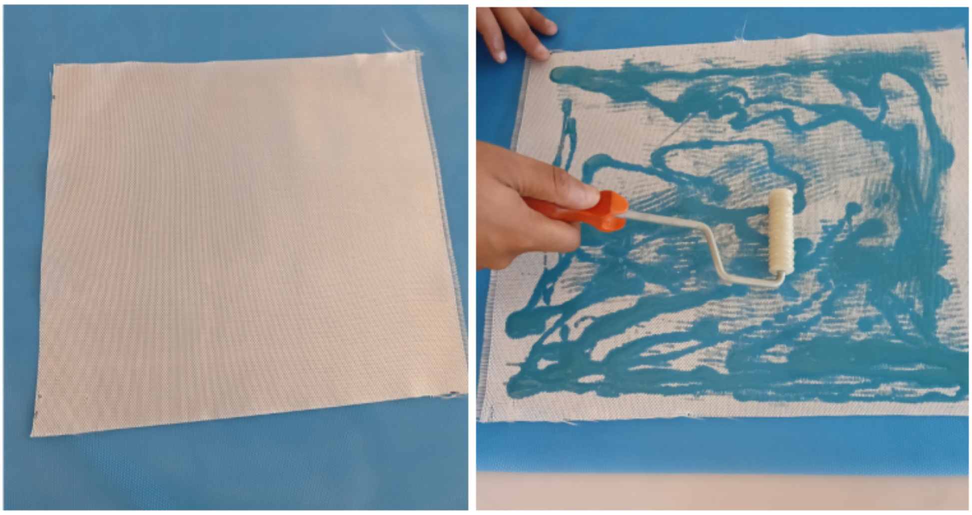


Figure 3.22: Fiberglass layering

- Pre-Preg storage: The 10 layers of fiberglass, which are already impregnated, were stored in a paper base while being maintained under refrigeration at -20° degrees Celsius. This temperature reduced the curing reaction rate, which protected the workability of the material until the next fabrication steps.

(a) (b)

Figure 3.23: Pre-Preg storage

- Vacuum pump : A vacuum pump, operated to extract air from the vacuum bag that encased the dielectric substrate. The role of removing air and excess resin through this procedure allowed the layers to bond closely. The process improved both the overall strength and the reliability of the composite material. Eliminating voids was essential because they could affect the dielectric properties of the substrate while increasing signal loss, changing the dielectric constant.

Figure 3.24: Vaccum pump

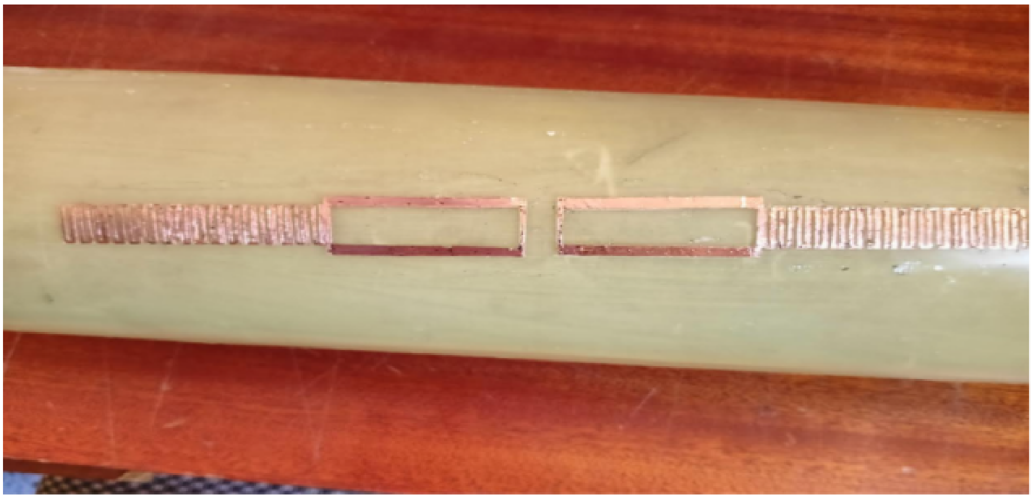
- The composite part needed the exact temperature and time to reach full rigidity and desired durability.

3.8.2 Antenna PCB fabrication process

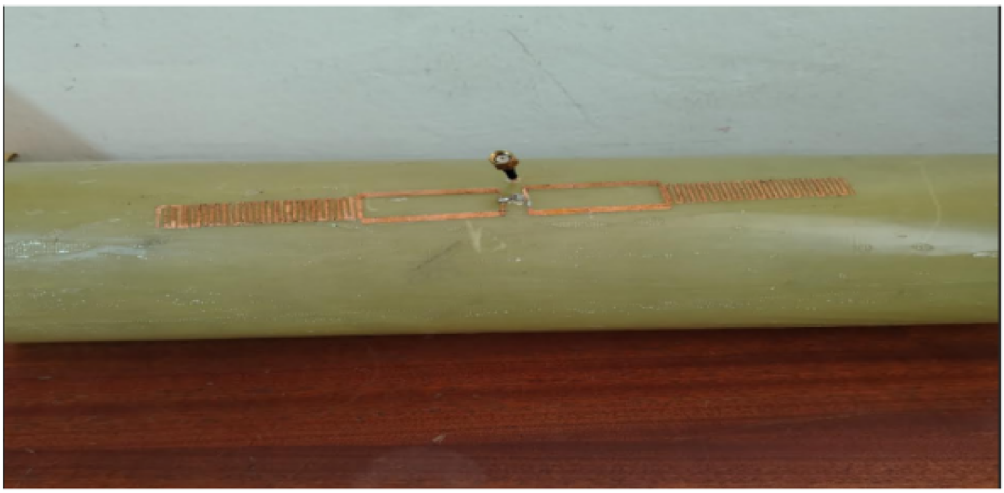
The simulated antenna design was exported from HFSS as a Gerber file to create the PCB layout, and the copper board was cut to the dimensions of the prototype using a shear. Using traditional photolithography, the PCB layout was placed on a presensitized board and exposed to ultraviolet light for 1 minute and 50 seconds, hardening the protected areas. The board was then developed in a chemical bath to remove the unexposed photosensitive layer, revealing the antenna pattern on the copper. Finally, the board was rinsed with water to stop the reaction and prepare it for subsequent processing.

3.8.3 Mounting antenna onto the substrate

- The antenna was fixed to the substrates, as shown in Figure a.
- The coaxial cable is used because it provides a controlled impedance transmission line, typically 50 ohms, which minimizes signal loss and reflections. The inner and outer conductors of the coaxial cable are connected to the dipole elements from within the substrate, and the entire coaxial cable then exits the substrate from the inside to the outside. This method helps maintain a low profile for the antenna and can protect the feeding line, as indicated in Figure b.



(a)



(b)

Figure 3.25: Dipole antenna realization

Measurement setup

In this measurement configuration, the fabrication of a copper antenna, mounted on a cylindrical dielectric substrate, is connected to the port of a Vector Network Analyzer (VNA) through a coaxial cable. This setup enables an accurate characterization of the electromagnetic performance of the antenna.

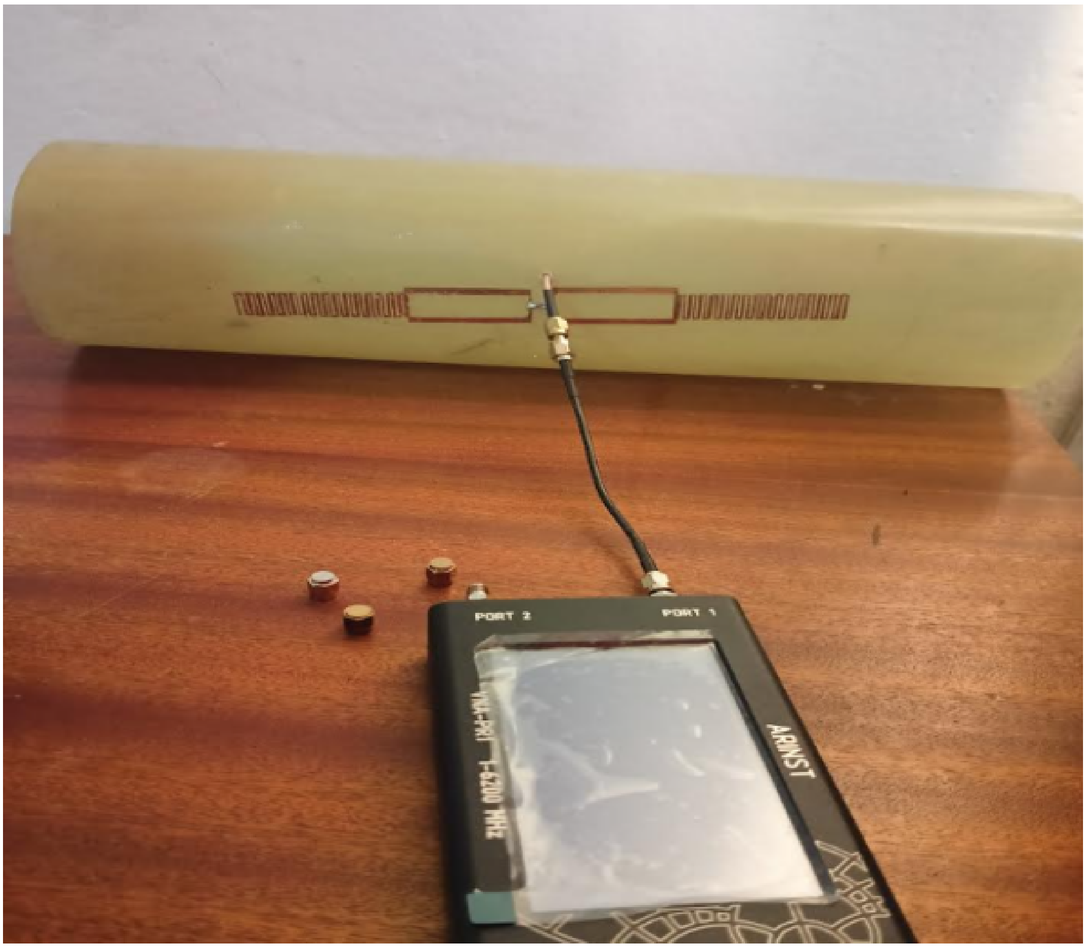


Figure 3.26: Antenna to VNA interface for measurement

3.8.4 Experimental results

The following figure presents the experimental results for antenna characterization, where a personal computer is used to display the S-parameter measurements obtained from a Vector Network Analyzer. The primary visualization includes the logarithmic magnitude S_{11} and the radiation pattern.

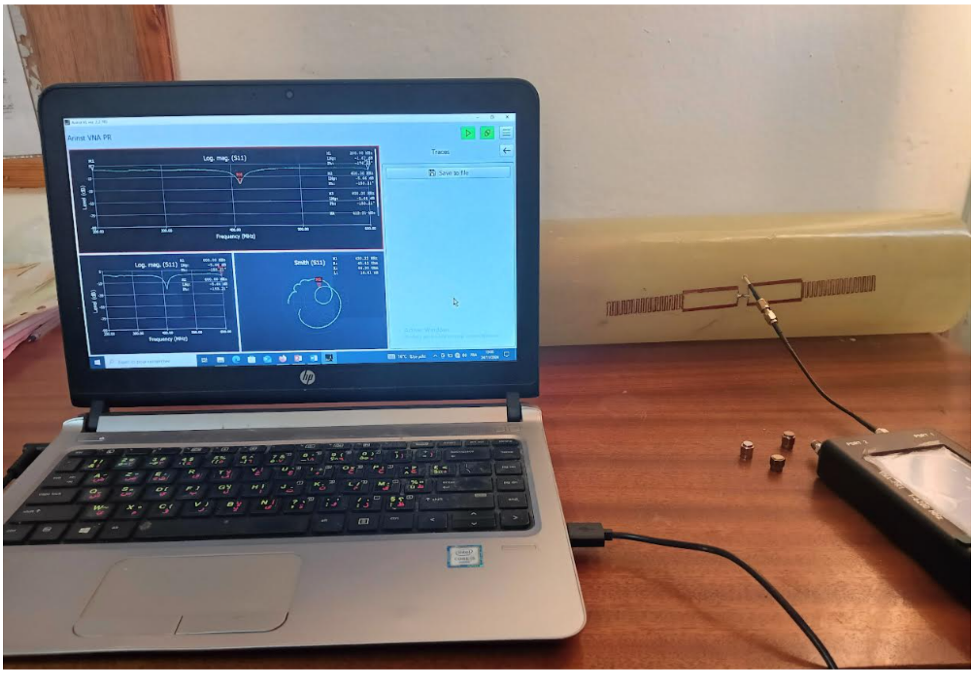


Figure 3.27: Visualization of experimental antenna

3.8.5 Measured results

S-Parameter

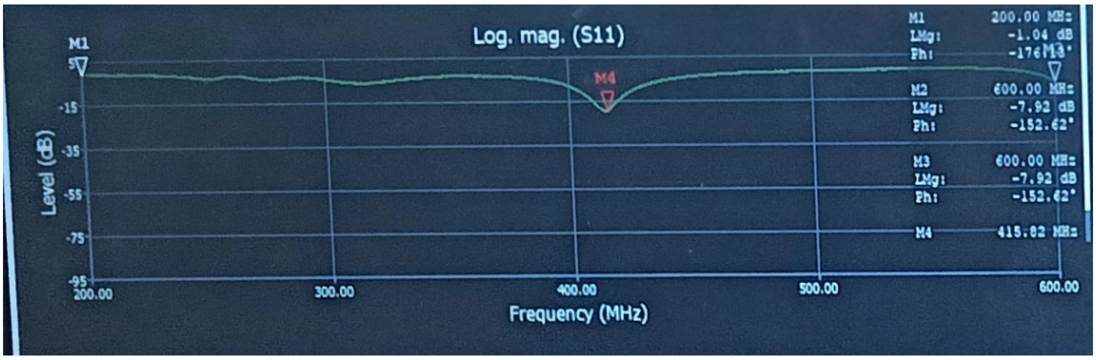


Figure 3.28: S-parameter result

From the results of the measurements in the S parameter, it is evident that only a small fraction of the incident power is reflected back to the antenna. This indicates efficient power transfer and good antenna matching. The following data demonstrate it:

The relationship between the return loss in dB ($S_{11\,(\mathrm{dB})}$) and the magnitude of the reflection coefficient ($|\Gamma|$) is given by:

$$S_{11\,(\mathrm{dB})} = 20\log_{10}|\Gamma|$$

where $|\Gamma|$ is the magnitude of the reflection coefficient.

Given an S_{11} of $-25\,\text{dB}$:

$$-25 = 20\log_{10}|\Gamma|$$

To find $|\Gamma|$, we rearrange the equation:

$$|\Gamma| = 10^{\frac{-25}{20}} \approx 0.0562$$

The percentage of power reflected is calculated as :

$$\text{Percentage of power reflected} = |\Gamma|^2 \times 100\% = (0.0562)^2 \times 100\% \approx 0.316\%$$

This implies that only 0.316% of the power is reflected and more than 99.684% of the power is transferred to or radiated by the antenna.

Radiation pattern

The radiation pattern was measured using a LAB VOLT test bench.

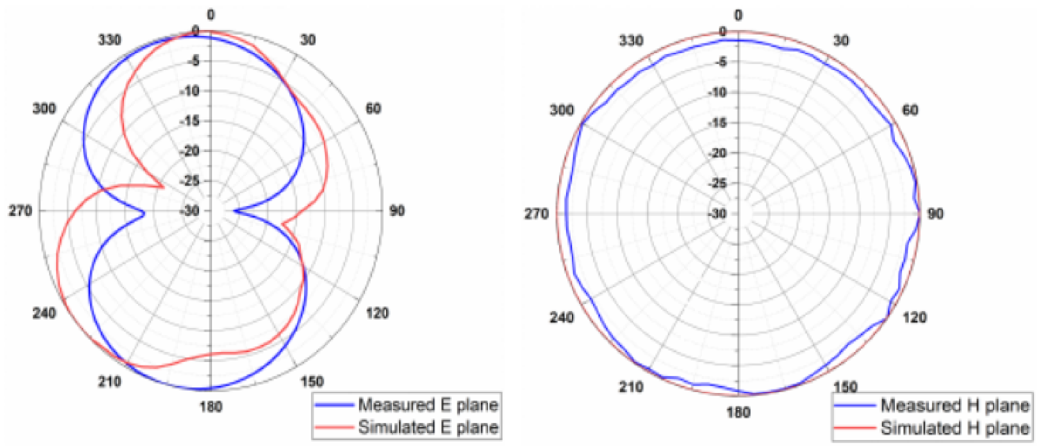


Figure 3.29: Radiation pattern

The plots compare the antenna's simulated and measured radiation patterns in the E- and H-planes.

Good agreement between these patterns confirms the antenna design. The E-plane shows a broad, quasi-omnidirectional pattern with dips (nulls), while the H-plane shows a more even, uniform radiation.

3.8.6 Synthesising results

- It is observed that there is a slight difference between the simulation and measurement results for the S-parameter. Specifically, the simulated value of S_{11} is $-30\,\text{dB}$, while the measured value (realization) is $-25\,\text{dB}$. This small discrepancy is completely normal and can be attributed to practical factors such as fabrication tolerances, material property variations, and measurement uncertainties that are inherent in real-world implementations but are often idealized or neglected in simulations.

- Radiation pattern plots demonstrate the antenna's directional behavior in the two main planes. The close agreement between the simulated and measured results indicates that the antenna design is effective and the simulation approach is reliable. In the E-plane, the antenna exhibits a more focused radiation pattern with noticeable nulls, while the H-plane shows a wider, almost omnidirectional pattern, which is beneficial for providing consistent coverage in the horizontal direction.

3.9 Antenna placement

Positioning the antenna within the outer wing of hybrid UAVs offers practical advantages during maintenance or repairs. This placement ensures that the antenna remains protected and, due to its compact nature, does not hinder access when addressing issues. In addition, it minimizes aerodynamic drag, preserving the overall aerodynamic efficiency of the drone.

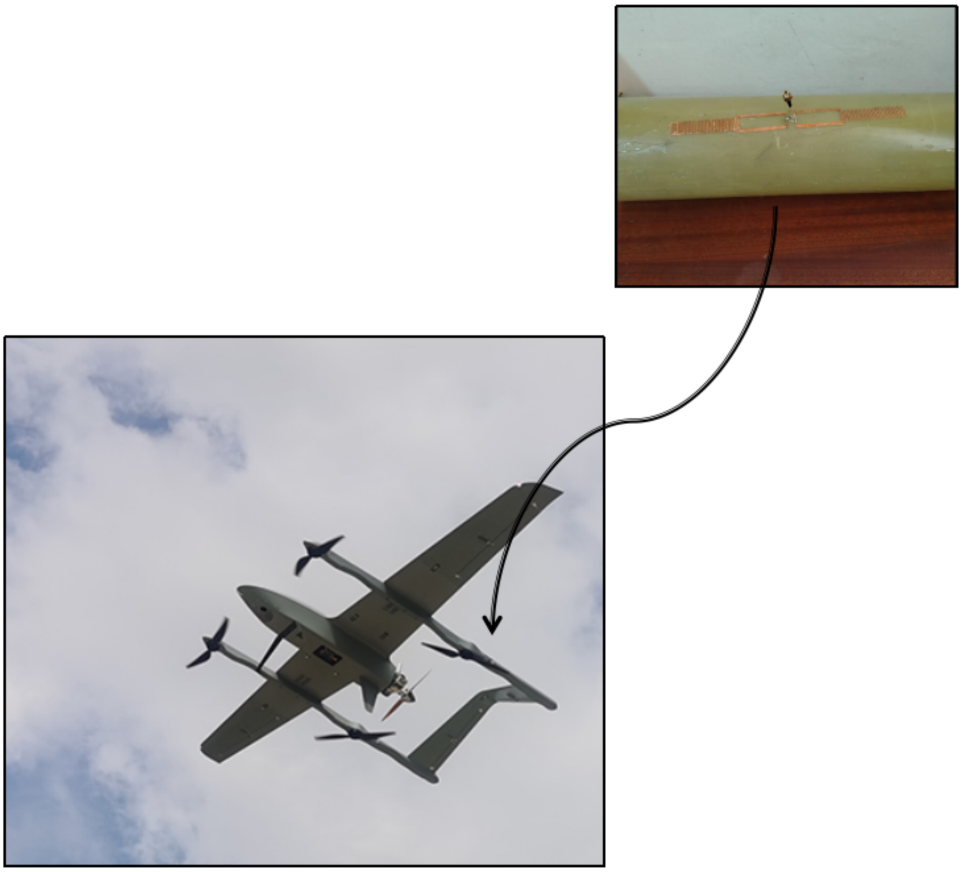


Figure 3.30: Antenna placement

3.10 Conclusion

This chapter has completely explored the comprehensive design and simulation of a miniature conformal antenna for hybrid drone telemetry applications. The evolution of the antenna, starting from a foundational printed dipole through a conformal antenna, systematically advanced to a miniaturized slotted structure with the size reduced by approximately 60%. This design methodology was strategically focused on achieving three objectives: miniaturization, conformability, and optimized antenna performance across the operational frequency band. These successful simulation results provide a clear theoretical and practical pathway for the antenna's realization and its comprehensive performance evaluation.

Overall, the fabrication achieved positive results, validating the design approach and confirming that the antenna performs satisfactorily under real-world conditions.

General Conclusion

This research presented an innovative solution that outperformed traditional antenna configurations in difficult radio frequency (RF) environments. It achieved improved signal quality and better data telemetry through a miniature conformal antenna with advanced substrate and metamaterial integration.

The developed high-performance antenna system provided essential communication benefits to UAVs through multiple operational advantages, enabling them to maintain stable data connections for essential real-time transmission. The design reduced interference susceptibility, allowing drones to maintain effective operations in crowded electromagnetic spectra while minimizing signal degradation.

In particular, implementation of a miniature conformal antenna, which is based on advanced substrate properties, solved the fundamental limitations of size, weight, and power in drone design.

For future work, the integration of electrically reconfigurable antennas is proposed to qualify dynamic adaptation of frequency, polarization, and radiation patterns, further enhancing communication and spectrum efficiency in complex operational environments.

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