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# Low-Cost 3-D Printed Helical Antenna with Dielectric Support

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A thesis

submitted in partial fulfillment of the  
requirements for the degree of

Master of Science

University of Washington

2024

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Program Authorized to Offer Degree:

Electrical Engineering

University of Washington

**Abstract**

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Satellite-based internet connection requires high directivity, millimeter wave phased array antennas to be able to receive and transmit signals effectively. Phased array antennas for millimeter waves have historically been very expensive to manufacture. Exploring low-cost methods for manufacturing high directivity antennas may bring down the costs of these systems, allowing more equitable access to internet.

Helical antennas are a type of high directivity antenna that can be used for these purposes. However, helical antennas are difficult to manufacture and scale due to its three dimensional (3-D) shape of the helix conductor. New 3-D printing technology allows the creation of a dielectric support for the helical antenna element. This adds mechanical rigidity to the antenna and is feasible for high volume manufacturing at a lower cost.

This thesis explores the design of a low-cost helical antenna using a 3-D printed dielectric core for mechanical support. The research in this thesis concludes that it is possible to design a helical antenna using low-cost dielectric materials with high relative permittivity at microwave frequencies. As a proof of principle, a 5 GHz helical antenna embedded in a solid dielectric was designed and modeled using electromagnetic field simulation software. At 5 GHz, the software simulations can be compared to helical antennas that are manufactured on conventional 3-D printers and commonly used resin dielectrics. The conclusion and results of the computer simulations show that helical antennas with dielectric support will radiate

in the axial mode with high directivity and circular polarization.

# TABLE OF CONTENTS

	Page
List of Figures . . . . .	ii
List of Tables . . . . .	iii
Glossary . . . . .	iv
Chapter 1: Introduction . . . . .	1
1.1 Friis Transmission Formula . . . . .	1
1.2 Phased Array Antennas . . . . .	4
Chapter 2: Background on Antennas . . . . .	6
2.1 Antenna Radiation Pattern Parameters . . . . .	6
2.2 Current Technology: Planar Patch Antennas . . . . .	9
Chapter 3: Design of Helical Antennas . . . . .	12
3.1 Background on Helical Antennas . . . . .	13
3.2 Helical Antennas in Axial Mode . . . . .	14
3.3 Simulation of a 5 GHz Helical Antenna . . . . .	17
Chapter 4: Helical Antenna with Dielectric Support Core . . . . .	24
4.1 Effective Wavelength . . . . .	25
4.2 Simulation with Dielectric Cylindrical Support . . . . .	26
Chapter 5: Conclusion and Future Work . . . . .	33
Bibliography . . . . .	34

## LIST OF FIGURES

Figure Number	Page
1.1 GEO vs LEO Satellite Orbits . . . . .	3
1.2 Near Field vs Far-Field of a Phased Array Antenna . . . . .	5
2.1 Polarization Ellipse of an Electric Field of a Wave Traveling Along the Z-Axis	8
2.2 Patch Antenna Diagram . . . . .	10
3.1 Dimensions of the Helical Antenna . . . . .	13
3.2 Normal Mode vs Axial Mode . . . . .	14
3.3 Phase Distribution of a $T_1$ Transmission Mode . . . . .	15
3.4 CST Model of 5 GHz Helical Antenna . . . . .	18
3.5 3-D Farfield Antenna Pattern . . . . .	19
3.6 Axial Ratio of 5 GHz Helical Antenna Simulation . . . . .	20
3.7 Return Loss of Helical Antenna (S11) . . . . .	21
3.8 1-D Pattern Cuts of the Helical Antenna . . . . .	22
4.1 5-Turn Helical Antenna with Dielectric Core . . . . .	26
4.2 3-D Far-field Pattern of Helical Antenna with Dielectric Core . . . . .	29
4.3 1-D Pattern Cuts of the Helical Antenna with Dielectric Core . . . . .	30
4.4 Axial Ratio of Helical Antenna with Dielectric Core . . . . .	31

## LIST OF TABLES

Table Number	Page
1.1 Friis Transmission Formula Parameters . . . . .	2
3.1 5-Turn 5 GHz Helical Antenna in Free Space . . . . .	17
3.2 Simulated Results of 5 GHz Antenna . . . . .	23
4.1 Effective Wavelength Calculation Results . . . . .	27
4.2 Dimensions of 5-Turn Helical Antenna with Dielectric Core . . . . .	28
4.3 Simulated Results of 5 GHz Antenna in Free Space vs with Dielectric Core .	32

## GLOSSARY

**ANTENNA GAIN:** The ratio of the radiation intensity in a given direction to the radiation intensity that would be produced if the power accepted by the antenna were isotropically radiated [6]

**AXIAL RATIO:** The ratio of the major and minor axis of a polarization ellipse

**DIELECTRIC:** Electric insulator that can be electrically polarized

**DIRECTIVITY:** The ratio of the radiation intensity in a given direction from the antenna to the radiation intensity averaged over all directions[6]

**EFFECTIVE APERTURE:** The ratio of the maximum effective area of the antenna to the aperture area

**EFFECTIVE PERMITTIVITY:** An estimation of the permittivity in a region where there are multiple mediums of different permittivities

**FAR-FIELD:** The region in which the observed radiation pattern does not change with distance, and there are only radiating electromagnetic fields

**FRIIS TRANSMISSION FORMULA:** Formula that gives the power received over a radio communication link

**GEOSYNCHRONOUS ORBIT (GEO):** Earth orbits that are synchronized to the rotation of the Earth on its axis

**HELICAL ANTENNA:** Antenna made of one more conducting helixes

**LOW EARTH ORBIT (LEO):** Earth orbits less than 2,000 kilometers from Earth's surface

**MICROSTRIP:** Metallic conductor bonded to a dielectric substrate used for transmitting radio frequency signals

**NEAR-FIELD:** Region near the antenna where the fields are reactive and radiating

PERMITTIVITY: Quantifies how well an electric field permeates through a medium

PHASE VELOCITY: The speed at which an electromagnetic wave moves through a medium

PHASED ARRAY ANTENNAS: An array of antenna elements where each antenna element has a variable phase and amplitude which allow for control of the beam direction and pattern shape

PLANAR PATCH ANTENNA: A planar patch antenna is a metal patch suspended over a ground plane, usually separated by a dielectric substrate

POLARIZATION: Polarization of an antenna describes the curve traced by the end point of the arrow (vector) representing the instantaneous electric field of the electromagnetic wave emitted by the antenna

RECIPROCITY: The antenna pattern for a transmitting antenna will be the same if the antenna is used as a receiving antenna

## ACKNOWLEDGMENTS

First, I would like to express my sincere appreciation to my advisor, Dr. Walter Charczenko, for mentoring and supporting me through my thesis research for the past year. I would not have been able to complete my research without his encouragement and advice. I also want to thank my supervisory committee members, Dr. Seungkeun Choi, who assisted me in 3-D printing my designs, and Dr. Tadesse Ghirmai, who reviewed and provided feedback on my thesis.

I must also thank Dr. Lee Paulsen and Dr. Zachary Miers for sparking my interest in researching antennas when I first started at Amazon's Project Kuiper, and also my colleagues Peter Hetzel, John Shamblin, Tim Kelley, and Jordan Doran for their mentorship as well.

I want to thank my parents and brother for encouraging me to pursue my education and supporting me along the way. And finally, I need thank my patient and kind fiance, Bryce, who still wants to marry me after I spent 4 years neglecting him to finish my degree.

## DEDICATION

Dedicated to Bryce, my loving fiance

## Chapter 1

# INTRODUCTION

As the internet becomes more important for education, jobs, and communication in general, access to high-speed broadband internet is crucial for equity and development of communities in the US and globally. Most cities and well-developed areas have access to the internet through fiber-optic cables, but it can be too expensive to install in rural areas or countries that lack infrastructure to install the cables. In the US, the Department of Transportation reports that it can cost up to \$105,600 per mile to install fiber [18]. The International Telecommunications Union (ITU) estimates that there are 2.9 billion people who do not have access to broadband internet, with 96% in developing countries [19]. To ensure equitable access, there needs to be a cheaper option for communities, which Low Earth Orbit (LEO) satellite constellations can provide. One of the most expensive and crucial system for these satellites systems is the antenna used to transmit and receive communication on Earth. Antennas for planes in similar use cases can cost around \$10,000 [16]. Lowering the cost of antennas is crucial to reduce overall system costs, which reduces costs on users, making internet more accessible.

### ***1.1 Friis Transmission Formula***

Satellites have been used for communications for decades and are now advanced enough to be used for high speed internet connections. Different communication satellites have their advantages and disadvantages. These can be compared using a satellite link budget using the Friis transmission formula.

The satellite link budget calculates how much power a satellite needs to transmit for the signal to be received on Earth, and vice versa. This is based on the Friis transmission

Description	Unit
Power from transmit antenna ( $P_t$ )	dBm
Power at receive antenna ( $P_r$ )	dBm
Effective aperture of receive antenna ( $A_{er}$ )	m <sup>2</sup>
Effective aperture of transmit antenna ( $A_{et}$ )	m <sup>2</sup>
Radius between transmit and receive antennas ( $r$ )	m
Wavelength ( $\lambda$ )	m

Table 1.1: Friis Transmission Formula Parameters

formula in Equation 1.1 with parameter in Table 1.1, which calculates the power received over a radio communication link.

$$\frac{P_r}{P_t} = \frac{A_{er}A_{et}}{r^2\lambda^2} \quad (1.1)$$

Friis transmission formula is the ratio of power received and power transmitted to the effective aperture of the respective antennas and the distance between the antennas. Effective aperture is the ratio of the maximum effective area of the antenna to the aperture area[6]. The Friis transmission formula defines how satellite communication links are designed to minimize the transmitted power needed receive the signal. Reducing transmit power is crucial to build Earth terminals that can run on lower power in more areas. Increasing the effective apertures of the antennas increases the power received in a communication.

### 1.1.1 Geosynchronous Satellites vs Low Earth Orbit Satellite Constellations

Satellite-based internet connection started with the first communications satellite launched by Telstar in 1962, with a non-geosynchronous orbit (non-GEO) that limited communications to 30 minutes every 2.5 hours of its orbit. The first GEO communication satellites were

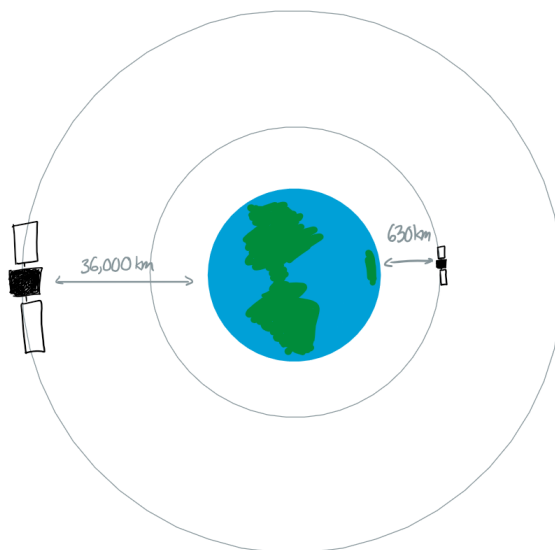


Figure 1.1: GEO vs LEO Satellite Orbits

launched a year later and could provide uninterrupted internet access to a large area on Earth using the bent-pipe communication method to connect users to internet gateways[8]. These satellites could provide internet over a large area at a lower cost than wired connections, but the latency is higher due to of the distance from Earth to the GEO satellites. GEO satellites orbit the earth at a height of 36,000 kilometers[1], which causes latency of about 916 milliseconds compared to cable internet's 46 milliseconds[3].

Reducing the satellite's distance from Earth reduces the latency of the communication link. Many modern satellite internet providers, such as SpaceX's Starlink, OneWeb, and Amazon's Project Kuiper, use a low earth orbit (LEO) satellite constellation system for this reason [5]. These LEO satellites constellations orbit at less than 700 kilometers from Earth's surface, which reduces latency by reducing the distance between the connection points. LEO satellites, unlike GEO, cannot stay stationary over an area above Earth, instead they orbit the Earth every 90 minutes at speeds of up to 17,000 miles per hour[7]. Several hundreds to thousands LEO satellites are used in a constellation to provide continuous internet access globally.

From Table 1, LEO satellites are shown to require much less power and smaller antennas to close the link between satellites in space and terminals on Earth. The drawback to LEO satellite constellations are that the internet connection terminals on Earth are much more complex. They need to be able to track the signal beam from a fast-moving satellite and capture enough of the signal energy to maintain a link. Phased array antennas can address both of these issues. These can be steered digitally with high precision and have high directivity. Phase array antennas are expensive to build but need to be manufactured at high volumes with low cost to have satellite-based internet be accessible to as many people as possible[16].

## **1.2 Phased Array Antennas**

### *1.2.1 Current Research in 3-D Printing Phased Array Antennas*

Phased array antennas are an array of antenna elements where each element is phase and amplitude variable. These antennas are highly configurable. Each of the individual antenna element beams add together to create one or more beams. In the region close to the antenna, called the near-field, the individual antenna elements' radiating fields combine destructively and constructively, resulting in a single highly directive beam when viewed from the far-field as seen in Figure 1.2. Far-field refers to the region in which the observed radiation pattern does not change with distance, and there are only radiating electromagnetic fields. Phased array antennas are steered electronically by offsetting the phases of adjacent antennas, which causes the beam in the far-field to change its pointing direction.

One area of research in phased array antennas focuses on three-dimensional (3-D) phased arrays. Most modern antennas are two-dimensional due to size restraints and ease of manufacturing, but 3-D antennas have more design flexibility. There has been research in using an additive 3-D manufacturing method called direct metal laser sintering (DMLS) to 3-D print antenna arrays, such as in 3-D Vivaldi antenna arrays and horn antenna arrays[14][12]. However, DMLS is very expensive and therefore may not scale well to mass manufacturing.

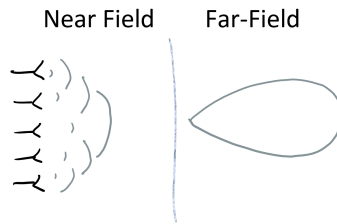


Figure 1.2: Near Field vs Far-Field of a Phased Array Antenna

Subtractive manufacturing has also been researched to build 3-D phased array antennas, but these antennas also require expensive machinery to make the high precision shapes needed for antenna arrays[9].

For this research, the focus was to explore a way to build a 3-D antenna with more accessible, low cost options. To reduce the complexity and scope for a thesis, only a single antenna element of the phased array was explored. Phased array antennas can be designed with nearly any antenna. Using an antenna element with a high effective aperture in a phased array increases the amount of power the phased array antenna can capture or radiate in one direction.

## Chapter 2

# BACKGROUND ON ANTENNAS

### 2.1 Antenna Radiation Pattern Parameters

An antenna is a transition device, or transducer, between a guided wave and a free-space wave, or vice versa, connecting transmission line circuits through free space [11]. Antenna patterns are three dimensional (3-D) representations of how energy radiates out of the antenna. The following terms are characteristics of antennas and terms used to describe antenna patterns.

#### 2.1.1 Reciprocity

Antennas are reciprocal devices which means an antenna will transmit with the same pattern it receives with. For this reason, transmit and receive are used somewhat interchangeably to describe antenna functions to make concepts easier to understand.

#### 2.1.2 Directivity

Directivity is defined as the ratio of maximum power density to its average value over a sphere as observed in the far field of an antenna, as represented in Equation 2.1, where  $P_{max}$  is the maximum power in a specific direction and  $P_{av}$  is the average radiated power distributed evenly across the sphere. In other words, directivity describes how an antenna focuses the radiated energy fed to the antenna.

$$D = \frac{P(\theta, \phi)_{max}}{P_{av}} \quad (2.1)$$

Directivity is unitless, but in practical measurement dBi, or decibels over isotropic, is

used. An isotropic antenna is an ideal antenna that radiates in all directions at the same power level.

Directivity can also be represented in relation to effective aperture,  $A_e$ .

$$D = \frac{4\pi A_e}{\lambda^2} \quad (2.2)$$

Thus, improving the directivity also improves the power ratio in the Friis transmission formula from the previous chapter.

### 2.1.3 Antenna Gain

Antenna gain is the actual quantity emitted or received by antenna because it includes any losses from the antenna structure or feed mismatches. The losses represented as the total antenna efficiency factor,  $k$ , multiplied with the directivity.

$$G = k * D \quad (2.3)$$

In practice, antenna gain is always less than directivity because  $k$  is always between 0 and 1. Antenna gain is not the same as amplifier gain because antennas are passive devices. Antennas cannot add power to incoming or outgoing signals.

### 2.1.4 Polarization

Polarization of an antenna describes the curve traced by the end point of the arrow (vector) representing the instantaneous electric field of the electromagnetic wave emitted by the antenna[2]. If the electromagnetic wave is traveling in a three dimensional space along the z-axis, the instantaneous electric field vectors can be represented in the x- and y- direction. This is represented with a polarization ellipse.

The axial ratio,  $AR$ , is the ratio between the minor and major axis of the polarization ellipse, as seen in Figure 2.1. The three main types of polarization are linear, elliptical, and circular. Linear polarization is when the vector only oscillates linearly in the x-y plane( $AR$

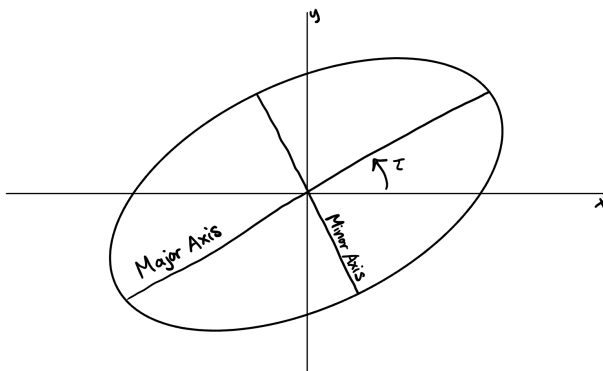


Figure 2.1: Polarization Ellipse of an Electric Field of a Wave Traveling Along the Z-Axis

= infinite). Elliptical is when the vector rotates in both the x- and y- axis. Circular is a special case of elliptical polarization when the vector rotates in x- and y- axis with the same magnitude.

Polarization is important to consider to maximize power transferred between antennas. Mismatched polarization of the receive and transmit antenna causes losses the communication link. This can be calculated using the difference in tilt angle,  $\tau$ , between the transmitting and receiving antennas to calculate the polarization matching factor,  $F$ .

$$F = \cos^2 \Delta\tau \tag{2.4}$$

This only applies to linear polarization, but can be used for elliptical polarization by separating the wave into two linearly polarized waves on the minor and major axis of the elliptical. If the tilt angle is  $0^\circ$ , the antennas are perfectly aligned, the matching factor would be 1, and all of the signal would be received. If the tilt angle is  $90^\circ$ , the matching factor would be 0, which means none of the signal would be received. This misalignment is avoided in antennas with circular polarization. For space based applications where orientation of the antennas with respect to each other cannot be tightly controlled, circular polarization is important to reduce loss in the link budget.

## **2.2 Current Technology: Planar Patch Antennas**

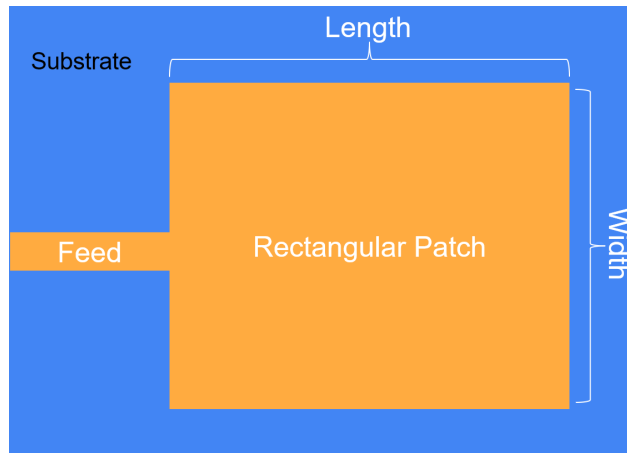
Planar patch antennas are the most widely manufactured antennas due to their relatively low cost and ease of manufacturing using existing printed circuit boards[11]. This section will introduce the basic concepts, benefits, and disadvantages of a rectangular patch antennas as a baseline for modern antennas.

### *2.2.1 Background on Planar Patch Antennas*

A planar patch antenna is a resonant antenna which operates by creating a standing wave along the antenna structure that radiates at a specific center frequency. Figure 2.2 shows a basic diagram of a rectangular patch antenna and its microstrip feed. The feed is where the antenna is connected to the rest of the RF circuitry for transmit or receive. The side labeled "Length" of the patch correlates to half of the wavelength of the center frequency, creating the resonance radiation. The side labeled "width" has minimal radiation in this configuration with one feed. Below the patch is a substrate layer, which separates the patch from the ground plane.

### *2.2.2 Directivity*

The directivity of the patch antenna cannot physically exceed 9 dB due its two dimensional (2-D) structure, and it requires a substrate with low relative permittivity to achieve [11]. Relative permittivity is how well electromagnetic waves can travel through a material compared to traveling through a vacuum. As the resonant frequency of the patch increase the permittivity also increases. Material that has low permittivity at high frequency is expensive because it requires a very uniform structure that needs specialty environments and equipment to manufacture. This reduces the cost effectiveness of patch antennas as frequencies increase.



(a) Top View



(b) Side View

Figure 2.2: Patch Antenna Diagram

### *2.2.3 Polarization*

As mentioned in the previous section, circular polarization is necessary for satellite communication. Rectangular patch antennas are naturally linearly polarized and require additional RF circuitry to be circular polarized. One of ways to circularly polarize a rectangular patch antenna is to use two feeds. One feed is along the "Length" and the other is along the "Width". These are fed the same signal 90° out of phase, using an 90° hybrid coupler, which excites two linearly polarized radiation modes that combine to create a circular polarization. The addition of the coupler adds design complexity and additional components to the antenna, reducing the cost benefits of the patch antenna.

## Chapter 3

### DESIGN OF HELICAL ANTENNAS

Helical antennas are a type of high directivity antenna that have been used in phased arrays for satellite communications since 1951[11]. Helical antenna arrays were used in low frequency applications for GPS and radio telescopes. Helical antennas are not used in most modern, high frequency arrays due to the difficulties in scaling the three-dimensional (3-D) design for mass manufacturing, especially compared to patch antennas which can use existing printed circuit board (PCB) manufacturing . The helical shape is not mechanically sturdy and can be easily bent. It is also more difficult to manufacture than two-dimensional patch antennas that are used today.

There are new 3-D printing technologies that can print dielectric materials with high precision, making it more feasible to print these types of antennas for millimeter wave applications, however this technology still uses expensive, propriety materials and printers. This thesis explores how adding a 3-D dielectric support to a helical antenna design affects its antenna pattern and how to adjust the design to accommodate for the support. It will be designed using a low cost off-the-shelf 3-D printer and resin at 5 GHz.

### 3.1 Background on Helical Antennas

Helical antennas were first proposed by John D. Kraus in 1947. Referencing Kraus's initial work on helical antennas[10], these symbols will be used to describe the dimensions of the helical antenna, which determine the frequency the helical antenna will resonant at.

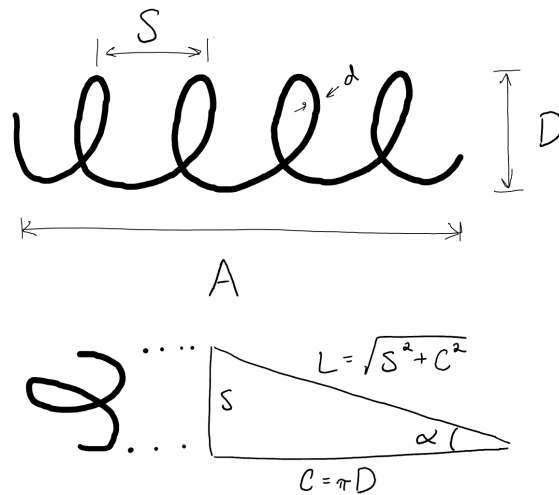


Figure 3.1: Dimensions of the Helical Antenna

$D$  = diameter of helix

$C = \pi D$  = circumference of helix

$S$  = spacing between turn

$\alpha$  = pitch angle =  $\arctan S/\pi D$

$L$  = Length of one turn

$n$  = number of turns

$A$  = axial length =  $nS$

$d$  = diameter of the helix conductor

$f_c$  = center or resonant frequency

$\lambda$  = wavelength of center or resonant frequency

The subscript  $\lambda$  will be used to signify when the dimension is a ratio to the wavelength. For example,  $D = \lambda$  can also be referred to as  $D_\lambda = 1$ .

### 3.2 Helical Antennas in Axial Mode

The helical antenna has two main modes of operation, normal mode and axial mode. In normal mode, the antenna pattern is more toroidal and isotropic, but in axial mode, the antenna has much higher directivity[11]. High directivity means the antenna can concentrate more of the total radiated power into one direction if transmitting, or if receiving, capture more of the radiated power coming in from one direction. These operation modes are based on the ratio of the dimensions of the helical antenna to the target resonant frequency's wavelength.

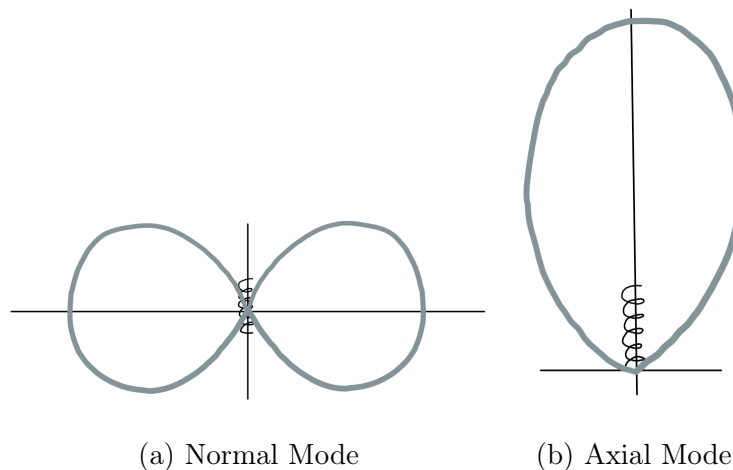


Figure 3.2: Normal Mode vs Axial Mode

Axial mode is when the direction of radiation is in the same direction as the helix. This type of antenna is called a traveling wave antenna, where the electromagnetic waves are guided along the antenna structure creating a current and voltage pattern across the antenna[2]. To achieve axial mode, the phase of the traveling wave along the antenna is

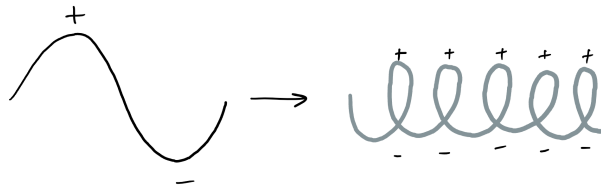


Figure 3.3: Phase Distribution of a  $T_1$  Transmission Mode

in-phase across each of the turns in the helix.

Figure 3.3 shows a simulation of a helical antenna's current patterns. At the resonant frequency, the positive currents will align axially along each turn. This is referred to as the  $T_1$  transmission mode and is primary transmission mode for helical antennas in axial mode [10]. Transmission modes, represented as  $T_m$  where  $m$  is an integer, are distinct current patterns that can occur along the antenna structure and depend on the ratio of helix dimension to the resonant frequency. Modes refer to the number of wavelengths of each turn. For  $T_1$  transmission mode, one turn is the same length as one wavelength.  $T_0$  is longer than one wavelength,  $T_2$  is two wavelengths per turn, and so on. Lower and higher order transmission modes create other antenna patterns that are somewhere in-between normal mode and axial mode. The dimensions required to create the  $T_1$  transmission mode is created when the length of one turn of the helix,  $L$ , is approximately equal to one wavelength of the resonant frequency.

The axial mode helical antenna design has many benefits for satellite communications. Due to its shape, it is naturally circularly polarized, unlike patch antennas which need special feed networks to be circularly polarized. The direction of circular polarization can be left or right-handed depending on the direction of the winding of the helix. The axial ratio ( $AR$ ) is ideally 1 (0 dB) for circular polarization and improves with the number of turns on a helical antenna. Below is the equation for the axial ratio.

$$AR = \frac{2n + 1}{2n} \quad (3.1)$$

where  $n$  refers to the number of turns in the helix[11]. As the number of turns increase, the

AR decreases closer to 1.

It is also a high directivity antenna, which, as mentioned in Chapter 1, increases the ratio of power received to power transmitted in a satellite communication link. Like  $AR$ , directivity of an antenna also increases with the number of turns.

$$Directivity = 12C_\lambda^2 n S_\lambda \quad (3.2)$$

$C_\lambda$  refers to the ratio of the circumference of the helical antenna to the wavelength of the center frequency,  $f_c$ .  $S_\lambda$  refers to the ratio of the spacing between turns to the wavelength, and  $n$  is the number of turns. This assumes the antenna is lossless. In practice, it will be lower.

While increasing the number of turns yields better  $AR$  and directivity, in practice, it is more mechanically difficult to support a very long helix. Also, the resistive losses in the conductor of the helix increases with a longer helix and distorts the transmission mode pattern, reducing the effectiveness of adding more turns to the helix.

On the other hand, having at least 4 turns reduces reflective losses because the reflected wave is attenuated greatly [10]. This is very useful in reducing tolerances for manufacturing because the input impedance can vary more and increases the bandwidth of the antenna. The terminal impedance,  $R$ , of a helical antenna when the number of turns,  $n$ , greater than or equal to 4 was determined to be within 20% of Equation 3.3.

$$R = 140C_\lambda \quad (3.3)$$

Equations 3.1 and 3.2 were derived from experimental testing, and only apply when the dimensions of the helical antenna meet the requirements in Equations 3.4 and 3.5.

$$0.8 < C_\lambda < 1.15 \quad (3.4)$$

$$12^\circ < \alpha < 14^\circ \quad (3.5)$$

The optimal circumference for a helical antenna to radiate in axial mode is about one wavelength, and the optimal spacing is around 0.2 to 0.4 times the wavelength or about a  $12^\circ$

to  $14^\circ$  the pitch angle,  $\alpha$ . Equation 3.4 can also be viewed as the estimate bandwidth of a helical antenna, with the antenna able to operate at 20% above and 15% below the center frequency.

### 3.3 Simulation of a 5 GHz Helical Antenna

Using the references from the previous section, a five-turn 5 GHz antenna was designed using requirements for axial mode from the previous section. The table below includes the dimensions of the helix dimensions.

Table 3.1: 5-Turn 5 GHz Helical Antenna in Free Space

Center Frequency ( $f_c$ )	5 GHz
Wavelength of $f_c$ ( $\lambda$ )	60 mm
Circumference of Helix ( $C$ )	60 mm
Ratio of Circumference of Helix to Wavelength ( $C_\lambda$ )	1
Diameter of Helix ( $D$ )	19.1 mm
Spacing Between Turns ( $S$ )	15 mm
Pitch Angle Between Turns ( $\alpha$ )	$14.0^\circ$
Total Length of Helix	61.8mm
Number of Turns ( $n$ )	5
Height of Helix ( $A$ )	75 mm
Diameter of Wire ( $d$ )	1 mm
Ground (PEC) Disc Size	45 mm

Five turns was chosen to reduce reflective losses. To radiate in axial mode at 5 GHz, the helical antenna circumference must meet the criteria from Equation 3.4, which is why the wavelength is equal to the circumference of the helix. The pitch angle also satisfies the

requirement from Equation 3.5.

The helical antenna was simulated in CST Studio Suite, a electromagnetic field simulation software, using the dimensions in Table 1 [17]. CST uses 3-D models and the electrical characteristics of materials in the model to simulate the antenna radiation patterns. In the simulation, the helix is modeled using a ideal Perfect Electrical Conductor (PEC), which is a idea lossless conductor. It is also connected to a  $140 \Omega$  coaxial cable to match the terminal resistance from Equation 3.3. The helix is grounded to an ideal PEC disc as the return path for the radiated electromagnetic fields. The PEC needs to have a diameter of at least  $3\lambda/4$  or 45 mm in this case for the antenna to see it as an infinite ground plane [11]. Figure 3.4 shows the model of the helical antenna in CST.

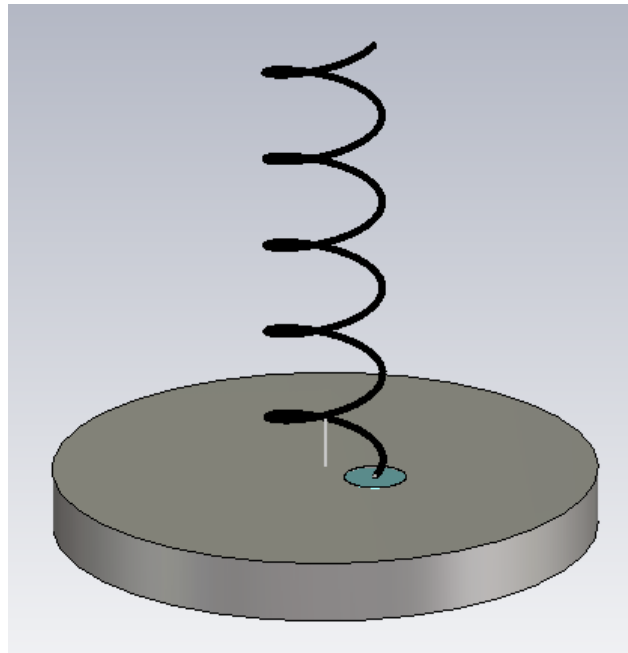


Figure 3.4: CST Model of 5 GHz Helical Antenna

Figure 3.5 shows the 3-D representation of the farfield pattern of the antenna. Table 3.2 shows the expected directivity and axial ratio calculated from Equations 3.2 and 3.1. Simulated results are expected to be worse than the calculated results because the calcu-

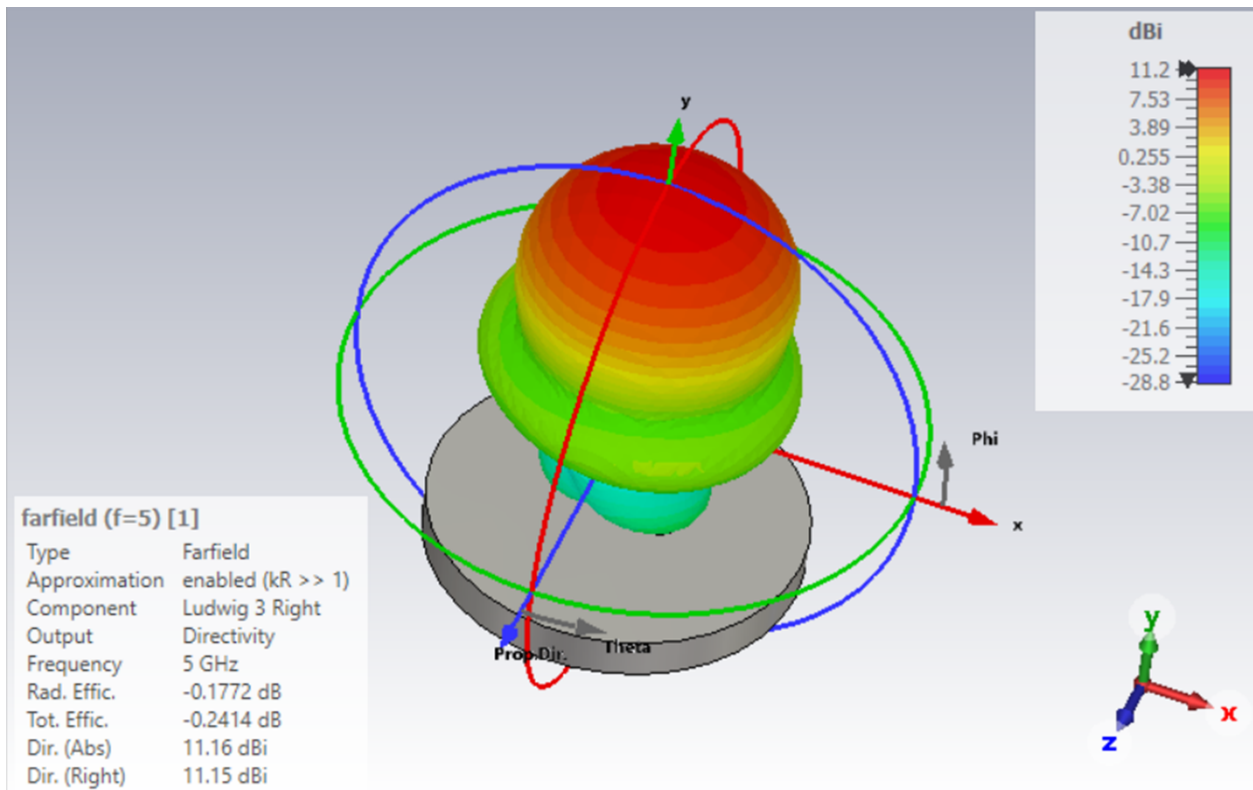


Figure 3.5: 3-D Farfield Antenna Pattern

lated results assume a perfect, lossless antenna. Directivity is marginally lower than the calculated results. This was due to the limits in resolution of the helix coil. The coil is not perfectly round but is modeled as cylindrical segments to reduce the computational load on the simulator. Initially, each turn contained fifteen segments, which yielded a result of 10.1 dBi (decibels over isotropic). Increasing the segments to thirty yielded the current result of 11.15 dBi, which is less than the calculated dBi by 0.65 dB. The calculated axial ratio is also very close to the simulated results, with only a 0.82 dB difference in major and minor axis.

Figure 3.6 shows the axial ratio of the 5 GHz antenna. The axial ratio is closest to 0 dB or perfect circular polarization at 5 GHz, but at 4 and 6 GHz, the axial ratio is higher at 1.4 and 1.65 dB respectively. This shows that axial ratio increases at the edges of the frequency bandwidth, which reduces the effective bandwidth of the antenna.

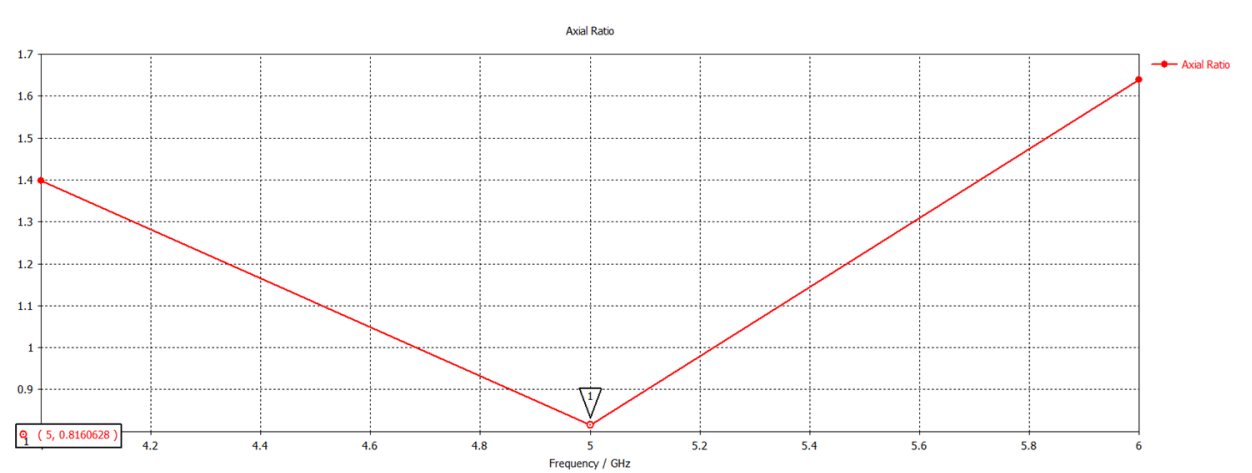


Figure 3.6: Axial Ratio of 5 GHz Helical Antenna Simulation

Input resistance to the helical antenna was designed in simulation to match the calculated input impedance in Table 3.2. This was done using a coax cable impedance equation that calculates the impedance based on the coax pin thickness, dielectric constant of the dielectric separating the pin and PEC disc, and the thickness of dielectric [13]. To gauge how well the input resistance matches the calculated value, the return loss of the antenna is shown in Figure 3.7. Return loss is a ratio of the reflected power to the input power to antenna, often referred to as the S11 measurement. A well-matched antenna will have low return loss. This simulated antenna had a low return loss of -18.3dB, which means that only 1.5% of the inputted power is reflected and 98.5% is transmitted. Return is also low at 4 to 6 GHz at below -16 dB, which shows that the antenna can support a large bandwidth. This is also seen in radiation efficiency of the antenna, which is how much of inputted power is not radiated by the antenna. Radiation efficiency is very low due to the matching the input impedance of the helical antenna and the lossless material used to model the helix.

While the model of the antenna is in a Cartesian coordinate system, a spherical coordinate system is used to describe the pattern. A spherical coordinate system describes the location of points in space based on a sphere, using  $r$  for the radius of the sphere,  $\theta$  for the angle in x-y

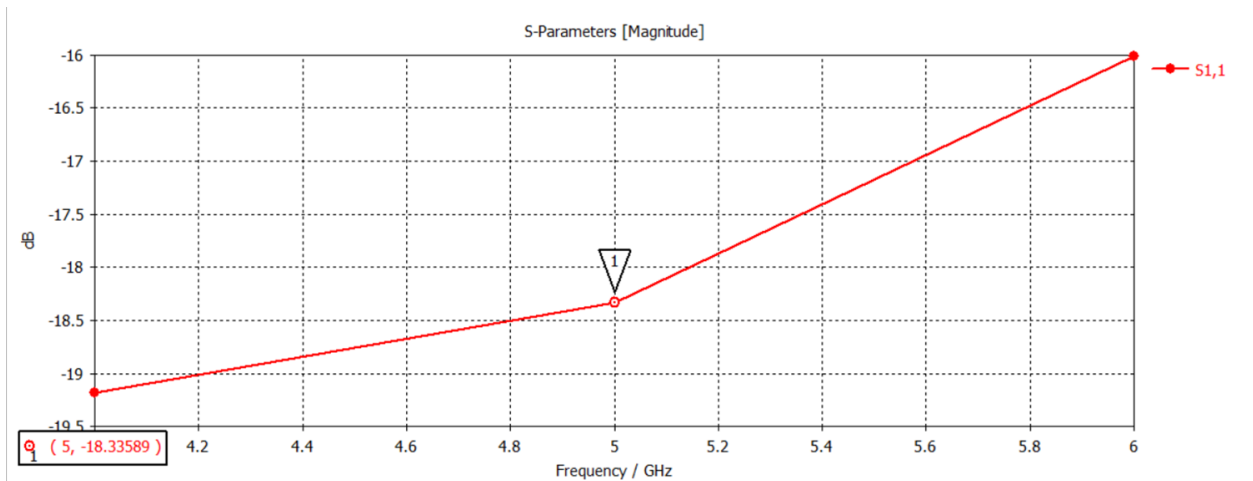
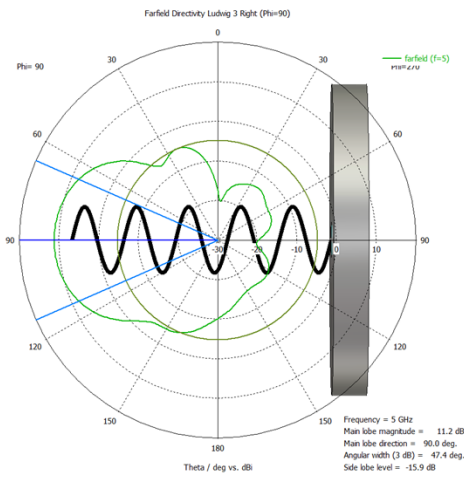


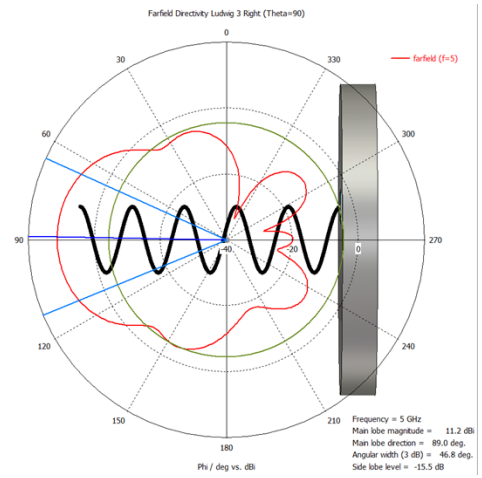
Figure 3.7: Return Loss of Helical Antenna (S11)

plane, and  $\phi$  for the angle y-z plane. Figures 3.8a to 3.8c show the resulting antenna pattern parallel to the antenna. The antenna is pointed along the positive y-axis or at  $\phi = 0^\circ$  and  $\theta = 90^\circ$ . The antenna pattern shows the directivity at 11.2 dBi or 13.0 times more directivity than an isotropic antenna. Main beam of the antenna is in line with the structure at 89 to 90 degrees. Side lobes, which are unwanted beams, are minimal with levels at -15.5 to -15.9 dB below the main beam.

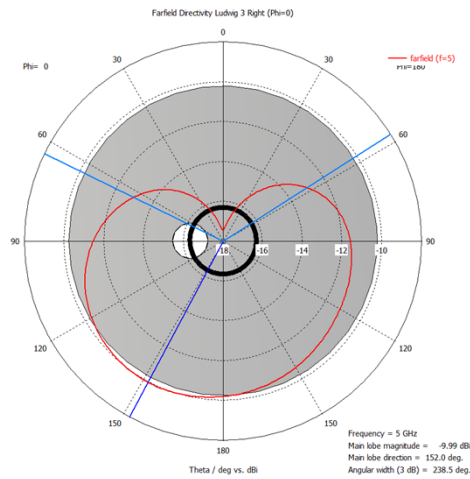
Figure 3.8a shows the antenna pattern from above the antenna structure. The beam is not perfectly uniform in this direction, varying from -10 dB to -18 dB, which is very low. In linear values, the beam only varies from 0.1 to 0.02 dBi.



(a)  $\phi = 90^\circ$



(b)  $\theta = 90^\circ$



(c)  $\phi = 0^\circ$

Figure 3.8: 1-D Pattern Cuts of the Helical Antenna

Table 3.2 shows the summary of the results of the simulation compared to the initial calculated results based on the design theory of a helical antenna. Overall, the simulation was shown to match theory and can be used as the base for exploring the addition of a mechanical support made from a dielectric in the next chapter.

<b>Antenna Parameters</b>	<b>Calculated Values</b>	<b>Simulated Values</b>
Directivity	11.8 dBi	11.15dBi
Radiation Efficiency	-	-0.17
Gain	-	10.98 dBi
Axial Ratio	0.414 dB	0.816 dB
Input Resistance	140 $\Omega$	140 $\Omega$
Reflection Coefficient (S11)	-	-18.3 dB

Table 3.2: Simulated Results of 5 GHz Antenna

## Chapter 4

### HELICAL ANTENNA WITH DIELECTRIC SUPPORT CORE

This following chapter builds upon the design principles of helical antennas to see the affects of adding a low-cost solid dielectric core to the helical antenna to add mechanical support. A dielectric core is important to use because it has a relatively high electromagnetic permittivity compared to other solid materials, which allows the electromagnetic waves radiate through the structure. Manufacturing dielectrics with high permittivity is very expensive because the material must have a very uniform structure, however low-cost dielectrics may be now accessible through 3-D printed resins.

Previous designs with thin-wall dielectric tubes as support have been used before [11]. Thin-walled dielectrics reduces the effective of the dielectric, but with reduced mechanically stability, especially at millimeter frequencies. At millimeter frequencies the wavelength is shorter, which would make the antenna smaller making it more difficult to build a electrically thin dielectric. This is why this design was explored with a solid core instead since the eventual goal is to scale to millimeter frequencies.

For this design, the dielectric support is a solid cylinder with grooves for the conducting coil of the helix. This can provide more mechanical support and act as a guide for building the antenna. Precise grooves in a cylinder may be difficult to manufacture with traditional methods, such as milling resin or creating molds, but with the advances in 3-D printing, this can be manufactured with a few hours of printing, which allows for faster prototyping and potentially scalable manufacturing in arrays.

### 4.1 Effective Wavelength

Adding material to any antenna will affect how the electromagnetic waves radiate. In a vacuum, the permittivity, or how easily electric fields permeates a space, is referred to as  $\epsilon_0$ , or free space permittivity and is used as the baseline [15]. Dielectric materials have relative permittivity,  $\epsilon_r$ , which is a ratio of the permittivity of the dielectric to the permittivity of free space. Relative permittivity is always positive value.

$$\text{Dielectric Permittivity} = \epsilon = \epsilon_r \epsilon_0 \quad (4.1)$$

When a dielectric material is added in the center of the helical antenna to provide mechanical support, this affects the phase velocity,  $v_p$  of the traveling wave due to the reduced permittivity of the material. Phase velocity is described as velocity of fixed point in a wave. As a visualization, if there was a single impulse of a sine wave traveling along a transmission line, the phase velocity would describe how long it took for the sine wave to travel a fixed distance along the line. The equation for phase velocity is given in Equation 4.2. From this equation, as relative permittivity increases, the phase velocity decreases.

$$v_p = \frac{1}{\sqrt{\epsilon_r \epsilon_0 \mu_0 \mu_r}} \quad (4.2)$$

The permeability of free space,  $\mu_0$ , and relative permeability,  $\mu_r$ , are not affected by the dielectric because it is not a magnetic material. Therefore  $\mu_r$  is equal to 1, and Equation 4.2 simplifies to Equation 4.3.

$$v_p = \frac{1}{\sqrt{\epsilon_r \epsilon_0 \mu_0}} \quad (4.3)$$

In free space,  $v_p$  is equal to the speed of light,  $c$ . To calculate the wavelength,  $\lambda$ , of the center frequency of the antenna in free space, the equation is simple.

$$\lambda = \frac{v_p}{f} = \frac{c}{f} \quad (4.4)$$

However, with the dielectric in the center of the antenna, the effective wavelength,  $\lambda_{eff}$  changes due to the change in phase velocity. A new effective wavelength must be calculated to maintain the  $T_1$  transmission mode for axial mode radiation, as mentioned in Chapter 3. This is done by estimating an effective permittivity,  $\epsilon_{eff}$ , based on the percentage the dielectric surrounds the conducting coil of the helix. This percentage is referred to as the fill factor,  $F$ . Equation 4.5 calculates the geometric mean using the fill factor and the relative permittivity of the dielectric.

$$\epsilon_{eff} = (1 - F) + F\epsilon_r \quad (4.5)$$

$\epsilon_{eff}$  can be used to calculate the phase velocity,  $v_p$ , replacing  $\epsilon_r\epsilon_0$  in Equation 4.2, then the effective wavelength can be calculated using Equation 4.6.

$$\lambda_{eff} = \frac{v_{peff}}{f} \quad (4.6)$$

## 4.2 Simulation with Dielectric Cylindrical Support

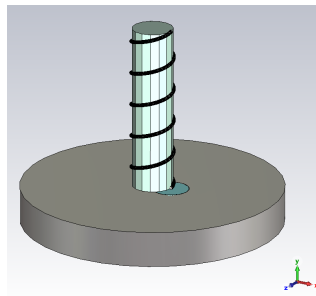


Figure 4.1: 5-Turn Helical Antenna with Dielectric Core

The simulation for this design is based off the simulation of the 5 GHz helical antenna in Chapter 3. The only change to the design is embedding the wire of the helix into a dielectric core and adjusting the dimensions for the helical antenna to match the new effective wavelength. The dielectric core used in this simulation is based off an available resin material

from the 3-D resin printer manufacturer, Formlabs, with the lowest relative permittivity,  $\epsilon_r$ , of 4.3 at 1MHz [4]. While this does not match the center frequency, the eventual goal is to build a physical model of the antenna for measurement using the Formlabs printer, so this will act as the starting point of the exploration.

Using the Equations 4.2 to 4.6 from the previous section, the effective wavelength for this antenna was calculated. The results are in Table 4.1. Only half of the wire used to make the helical antenna is embedded in the dielectric core, so the fill factor,  $F$ , is 0.5. The effective relative permittivity,  $\epsilon_{eff}$ , was then calculated using  $F$  and  $\epsilon_r$ . The effective phase velocity,  $v_{peff}$ , is calculated using Equation 4.3, which can finally be used to calculate the effective wavelength,  $\lambda_{eff}$ .  $\lambda_{eff}$  is shorter than the wavelength in free space due to the higher effective permittivity. This causes the electromagnetic wave to slow down, but the frequency of the wave stays the same, therefore reducing  $\lambda_{eff}$  and the size of the helical antenna.

Parameter	Value
Free Space Permittivity ( $\epsilon_0$ )	8.85 x 10 <sup>-12</sup> Farads * meter
Relative Permittivity of Dielectric ( $\epsilon_r$ )	4.3
Free Space Permeability ( $\mu_0$ )	1.26 x 10 <sup>-6</sup> Newtons * Amp
Relative Permeability ( $\mu_r$ )	1
Fill Factor ( $F$ )	0.5
Effective Relative Permittivity ( $\epsilon_{eff}$ )	2.65
Effective Phase Velocity ( $v_{peff}$ )	1.84 x 10 <sup>8</sup> m/s
Effective Wavelength ( $\lambda_{eff}$ )	37 mm

Table 4.1: Effective Wavelength Calculation Results

Table 4.2 contain the dimensions for the antenna design in Chapter 3 compared to the helical antenna with half of the wire embedded into a dielectric core using the  $\lambda_{eff}$ . The ratios for circumference and spacing are the same as the 5 GHz helical antenna in the previous

chapter.

<b>Antenna Dimensions</b>	<b>5 GHz Antenna in Free Space</b>	<b>5 GHz Antenna with Dielectric Core</b>
Center Frequency ( $f_c$ )	5 GHz	5 GHz
Wavelength of $f_c$ ( $\lambda$ )	60 mm	60 mm
Effective Wavelength ( $\lambda_{eff}$ )	60 mm	37 mm
Circumference of Helix ( $C$ )	60 mm	37 mm
Ratio of Circumference to Effective Wavelength ( $C/\lambda$ )	1	1
Diameter of Helix ( $D$ )	19.1 mm	11.8 mm
Spacing Between Turns ( $S$ )	15 mm	9.25
Pitch Angle Between Turns ( $\alpha$ )	14.0°	14.0°
Total Length of Helix Wire ( $L$ )	309 mm	191 mm
Number of Turns ( $n$ )	5	5
Height of Helix ( $A$ )	75 mm	46.25 mm
Diameter of Wire ( $d$ )	1 mm	1 mm
Ground (PEC) Disc Size	45 mm	27.75 mm

Table 4.2: Dimensions of 5-Turn Helical Antenna with Dielectric Core

#### 4.2.1 Simulation Results

The results of the simulation show that the antenna is still highly directive with good circular polarization with the dielectric core. Figure 4.2 shows the 3-D representation of the far-field pattern, with the antenna pointing along the y-axis. The directivity is still high at 8.93 dBi or 7.8 times more directive than an isotropic antenna, but it is reduced by 2.2 dB compared to the antenna operating in free space. This is likely due to errors in the estimation of the effective relative permittivity.

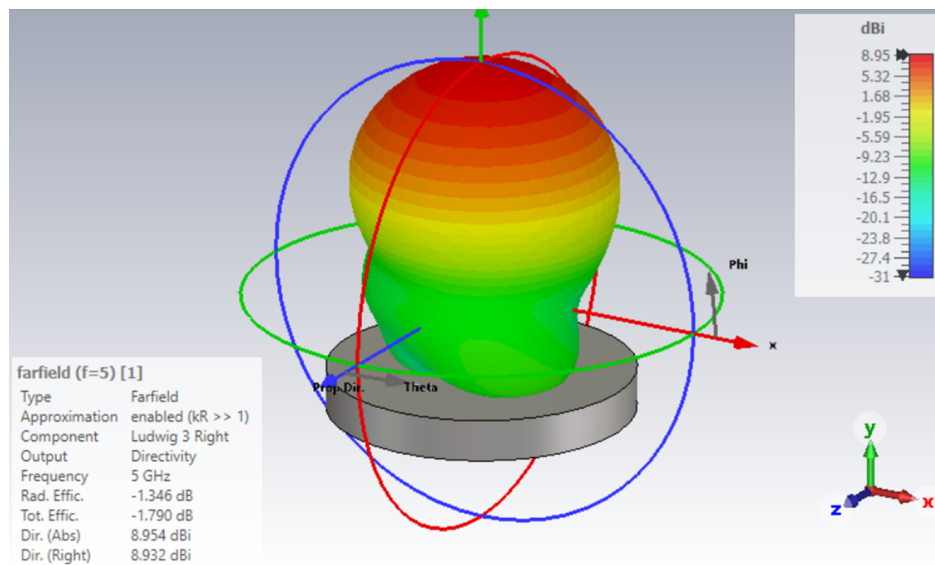
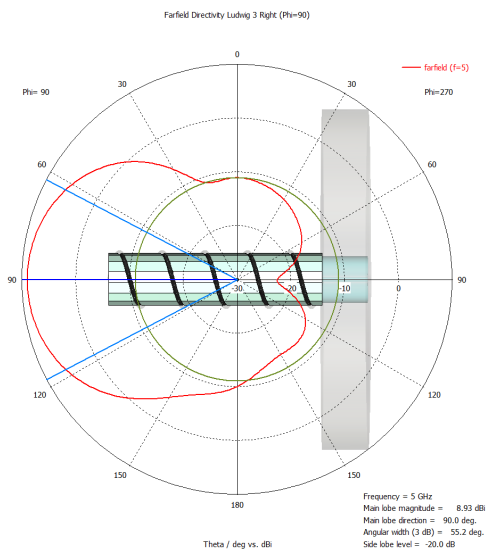
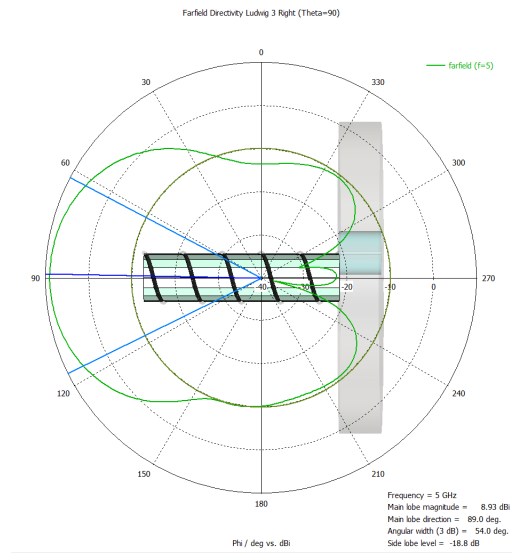


Figure 4.2: 3-D Far-field Pattern of Helical Antenna with Dielectric Core

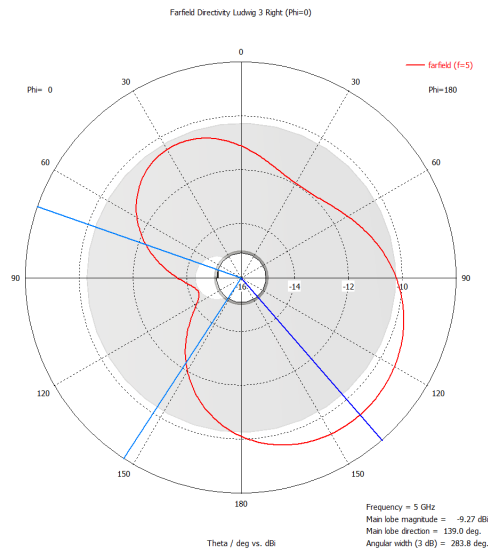
Figure 4.3 shows additional one dimensional (1-D) pattern cuts at angles  $90^\circ$  apart. The  $\phi = 90^\circ$  and  $\theta = 90^\circ$  plots show that the pattern is very symmetrical. The patterns also show there is no excessive tilt in the main lobe and is within  $0^\circ$  to  $1^\circ$  of the intended end-fire direction of the antenna along the y-axis. The  $\phi = 0^\circ$  plot shows that the pattern is also symmetrical about the y-axis, with variation from only -10 dB to -14 dB.



(a)  $\phi = 90^\circ$



(b)  $\theta = 90^\circ$



(c)  $\phi = 0^\circ$

Figure 4.3: 1-D Pattern Cuts of the Helical Antenna with Dielectric Core

The axial ratio is still close to circular polarization, or 0 dB, at 1.25 dB, as seen in Figure 4.4 which is slightly higher than the free space antenna by 0.434 dB. Figure 4.4 shows the axial ratio at 4, 5, and 6 GHz, with the axial ratio at 5 GHz being the closest to circular polarization. The axial ratio at 4 and 6 GHz are very high at 6 dB and 3.75 dB, which indicates that circular polarization will degrade as the frequency shifts farther from the center frequency. This is much larger than the antenna in free space from simulation in Chapter 3, where the 4 and 6 GHz axial ratio were within 1.2 dB of the 5 GHz axial ratio. This indicates that bandwidth of the antenna with the dielectric is reduced because it cannot support circular polarization across the same bandwidth as in free space.

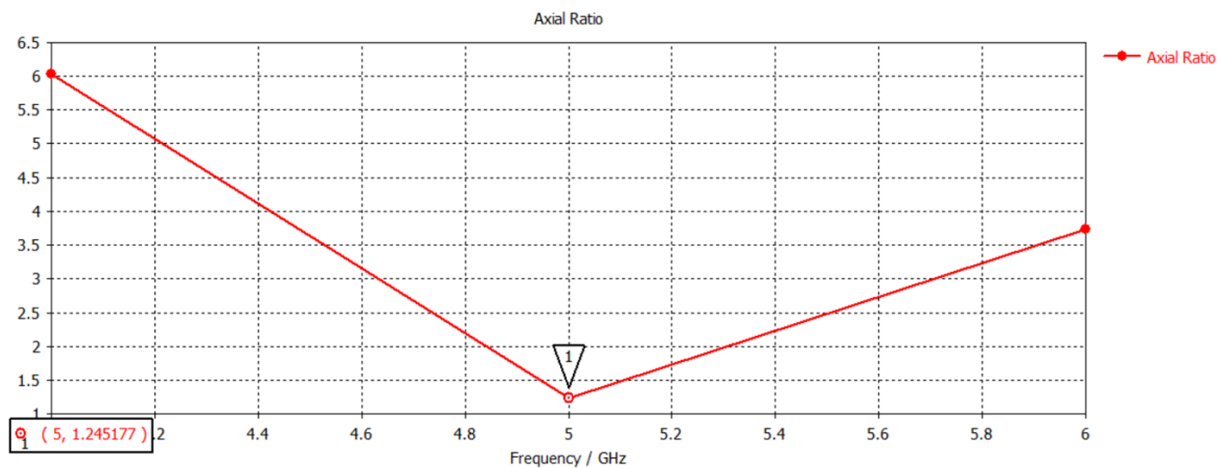


Figure 4.4: Axial Ratio of Helical Antenna with Dielectric Core

#### 4.2.2 Comparison with Antenna Design in Free Space

Table 4.3 compares the results of the simulation of the helical antenna from Chapter 3 to the helical antenna embedded in a dielectric core. Overall, the inclusion of the dielectric does reduce the directivity and the axial ratio of a helical antenna, however, it has physical benefits of adding mechanical rigidity to the design and also reduces the size of the antenna by over a quarter of the footprint. A smaller, less directive antenna in a phased array configuration can

be more directive than larger, more directive antennas because more of the smaller antenna elements can fit in to the same area compared to the larger antennas. The return loss of the helical antenna with the dielectric is also higher, which indicates that Equation 3.3 no longer applies. Radiation efficiency also decreases due to the increased return loss. This return loss may be reduced by using the now known return loss value and the input resistance of  $140\Omega$  to match the new impedance of this antenna.

<b>Antenna Parameters</b>	<b>Calculated Values - Antenna in Free Space</b>	<b>5 GHz Antenna in Free Space</b>	<b>5 GHz Antenna with Dielectric Core</b>
Directivity	11.8 dBi	11.15dBi	8.93dBi
Radiation Efficiency	-	-0.17 dB	-1.35 dB
Gain	-	10.98i dB	7.58 dBi
Side Lobe Level	-	-15.9 dB	-20.0 dB
Axial Ratio	0.414 dB	0.816 dB	1.25 dB
Input Resistance	$140\ \Omega$	$140\ \Omega$	$140\ \Omega$
Reflection Coefficient (S11)	-	-18.3 dB	-10.1 dB

Table 4.3: Simulated Results of 5 GHz Antenna in Free Space vs with Dielectric Core

## Chapter 5

### CONCLUSION AND FUTURE WORK

The conclusion of this thesis is that it is possible to design a high directivity helical antenna with the conducting wire of the helix embedded in a cylindrical mechanical support made of a high permittivity low-cost dielectric. The performance of this dielectric helical antenna is reduced compared to a helical antenna in free space, however, because of the smaller size of the dielectric helical antenna, it may be more directive in a phased array configuration. There are also additional optimizations that can be done in simulation to improve directivity of this antenna. The effective permittivity of the antenna can be more accurately estimated by reviewing the electric fields around the helical coil in simulation. The reflection coefficient can also be improved by calculating the change in the terminal resistance of the antenna with the dielectric core, which can then be used to match the feed of the antenna.

The next step in this design process is to measure the 5 GHz antenna designed with and without the cylindrical support. The antenna can be assembled using a 3-D printed cylinder as a guide to wrap an 18 gauge wire around. A copper plate with a pin feed SMA connector can be used as the disc and coax connector from the simulation. This can be measured in an anechoic chamber with a vector signal analyzer (VNA) to measure the antenna pattern. The VNA can also be used to measure the S11 of the antenna. These measurements can be used to verify how accurate the simulated design compared to the physical antenna design.

## BIBLIOGRAPHY

- [1] The European Space Agency. *Types of orbits*. 2020. URL: [https://www.esa.int/Enabling\\_Support/Space\\_Transportation/Types\\_of\\_orbits#:~:text=Low%20Earth%20orbit%20\(LEO\)&text=Unlike%20satellites%20in%20GEO%20that,their%20plane%20can%20be%20tilted](https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#:~:text=Low%20Earth%20orbit%20(LEO)&text=Unlike%20satellites%20in%20GEO%20that,their%20plane%20can%20be%20tilted). (visited on 04/06/2024).
- [2] Constantine A. Balanis. *Antenna Theory Analysis and Design*. 3rd. Hoboken, New Jersey: John Wiley & Sons, Inc., 2005.
- [3] Stephen Cobb. *Satellite Internet Connection for Rural Broadband: Is it a viable alternative to wired and wireless connectivity for America's rural communities?* May 2011. DOI: 10.13140/RG.2.2.26033.74083.
- [4] Formlabs. *PU Rigid 1000 Resin*. 2024. URL: <https://formlabs.com/store/materials/pu-rigid-1000-resin/> (visited on 03/10/2024).
- [5] Business Strategy Hub. *Top 10 Starlink Competitors and Alternatives*. 2024. URL: <https://bstrategyhub.com/starlink-competitors-and-alternatives/> (visited on 04/07/2024).
- [6] "IEEE Standard for Definitions of Terms for Antennas". In: *IEEE Std 145-2013 (Revision of IEEE Std 145-1993)* (2014), pp. 1–50. DOI: 10.1109/IEEESTD.2014.6758443.
- [7] Amazon.com Inc. *How Amazon's Project Kuiper is building satellites to survive extreme conditions in space*. 2022. URL: <https://www.aboutamazon.com/news/innovation-at-amazon/how-amazons-project-kuiper-is-building-satellites-to-survive-extreme-conditions-in-space> (visited on 04/14/2024).

- [8] Tori Kimball. *SKYTRAC #SatcomSeries: A Brief History of Satellite Communications*. 2022. URL: <https://www.skytrac.ca/resources/magazine/skytrac-satcomseries-a-brief-history-of-satellite-communications/> (visited on 04/06/2024).
- [9] Rick W. Kindt, John T. Logan, and M. Wajih Elsallal. “Machined Metal FUSE Array Apertures”. In: *2019 IEEE International Symposium on Phased Array System & Technology (PAST)*. 2019, pp. 1–4. DOI: 10.1109/PAST43306.2019.9021101.
- [10] J.D. Kraus. “The Helical Antenna”. In: *Proceedings of the IRE* 37.3 (1949), pp. 263–272. DOI: 10.1109/JRPROC.1949.231279.
- [11] John D Kraus and Ronald J Marhefka. *Antennas and Wave Propagation*. 4th. McGraw Hill Education, 2002.
- [12] Yujian Li et al. “3-D Printed High-Gain Wideband Waveguide Fed Horn Antenna Arrays for Millimeter-Wave Applications”. In: *IEEE Transactions on Antennas and Propagation* 67.5 (2019), pp. 2868–2877. DOI: 10.1109/TAP.2019.2899008.
- [13] Pasternack. *Coaxial Cable Impedance Calculator with Formula*. 2021. URL: <https://www.pasternack.com/t-calculator-coax-cutoff.aspx> (visited on 04/28/2024).
- [14] Carl Pfeiffer, Jeffrey Massman, and Thomas Steffen. “3-D Printed Metallic Dual-Polarized Vivaldi Arrays on Square and Triangular Lattices”. In: *IEEE Transactions on Antennas and Propagation* 69.12 (2021), pp. 8325–8334. DOI: 10.1109/TAP.2021.3083795.
- [15] David M. Pozar. *Microwave Engineering*. 4th. Hoboken, New Jersey: John Wiley & Sons, Inc., 2012.
- [16] Roger J. Rusch. *Op-ed / What could happen to the LEO broadband constellations?* 2021. URL: <https://spacenews.com/op-ed-what-could-happen-to-the-leo-broadband-constellations/> (visited on 05/20/2024).

- [17] Dassault Systemes. *CST Studio Suite*. 2024. URL: <https://www.3ds.com/products/simulia/cst-studio-suite> (visited on 04/28/2024).
- [18] United States Department of Transportation. *Roadside Telecommunications (RS-TC) Fiber Optic Cable Installation*. 2022. URL: <https://www.itskrs.its.dot.gov/decision-support/cost-plot/roadside-telecommunications-rs-tc-fiber-optic-cable-installation> (visited on 04/06/2024).
- [19] International Telecommunications Union. *Facts and Figures 2021: 2.9 billion people still offline*. 2021. URL: <https://www.itu.int/hub/2021/11/facts-and-figures-2021-2-9-billion-people-still-offline> (visited on 05/27/2023).