A Ridge-fed Conical Horn Antenna for Small Satellites

Arjun Gupta

Follow this and additional works at: http://digitalrepository.unm.edu/ece_etds

Recommended Citation
Arjun Gupta
Candidate

Electrical and Computer Engineering
Department

This thesis is approved, and it is acceptable in quality and form for publication:

Approved by the Thesis Committee:

Professor Christos G. Christodoulou, Chairperson

Professor Mark Gilmore

Dr. Joseph Constantine
A Ridge-fed Conical Horn Antenna for Small Satellites

by

Arjun Gupta

Bachelor of Technology, West Bengal University of Technology, 2008

THESIS

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science
Electrical Engineering

The University of New Mexico

Albuquerque, New Mexico

December, 2015
Dedication

To my family and friends.
Acknowledgments

I am grateful to my adviser, Professor Christos G. Christodoulou, for his support, encouragement and for providing me with everything I needed to get my degree and more. My sincere appreciation to Dr Joseph Constantine for conceiving the project and making me a part of it and guiding me through. I would like to thank Prof. Mark Gilmore for teaching me Microwave Engineering and for allowing me work in his shop to do my fabrications and taking time out to be on my committee.

A special thanks to Mr Firas Ayoub for letting me bounce ideas of him.

I am thankful to everybody at the Antennas and Computational Electromagnetics Lab and Electrical and Computer Engineering department, UNM. I would like to think that I have acquired something valuable from each individual I have worked with. I look forward to sharing my skills, ideas, and talents to benefit engineering sciences and in building a better future for humanity.
A Ridge-fed Conical Horn Antenna for Small Satellites

by

Arjun Gupta

Bachelor of Technology, West Bengal University of Technology, 2008
M.S., Electrical Engineering, University of New Mexico, 2015

Abstract

The increased popularity of small satellites such as CubeSats as an alternative vehicle for efficient and low cost space exploration has revolutionized the space research industry. The small physical size and other constraints owing to outer space applications has presented a myriad of exciting opportunities for antenna engineers to come up with alternative solutions to meet the ever evolving needs of the CubeSat applications. The advancement of technology has enabled small satellites to carry out sophisticated missions such as space weather monitoring, space telescopes, imaging and relaying of information from distant satellites. Advanced applications require a high speed downlink with base station for data transfer. The focus of the thesis is to design and develop a wide band antenna spanning a frequency spectrum from 2GHz to 13GHz. The design must exhibit circular polarization and drive a gain equal to or more than 10dB with a certain beamwidth. Mechanical attributes of a practical deployment mechanism has to be taken into consideration to make the design robust for autonomous deployment once on orbit.
# Contents

**List of Figures**

**List of Tables**

## 1 Introduction

1.1 Overview ................................. 1

1.2 Motivation for Ridge-fed Conical Horn .......... 4

1.3 Thesis Contribution ........................ 6

## 2 Background: Previous Research

2.1 Dipoles/Monopoles ........................ 8

2.2 Helical Antennas .......................... 9

2.3 Log Periodic Dipole Array .................. 13

2.4 Conical log spiral ........................ 14

## 3 Antenna Concept and Design

16
Contents

3.1 Horn Antenna ................................................................. 17

3.2 Conical Horn Theory ...................................................... 19
  3.2.1 Circular Waveguide .................................................. 20
  3.2.2 Conical Horn Flare ................................................. 22

3.3 Conventional Conical Horn Antenna ................................. 28
  3.3.1 Bandwidth ............................................................. 28
  3.3.2 Polarization .......................................................... 29
  3.3.3 Antenna Material ................................................... 29
  3.3.4 Antenna Feed ....................................................... 30

3.4 Ridge Design .............................................................. 30

3.5 Quad-ridge Open Boundary ............................................ 41

3.6 Ridge-fed Conical Horn Antenna ..................................... 50

4 Antenna Fabrication & Measurement .................................. 56
  4.1 Prototype X ............................................................... 56
    4.1.1 Measurement and Results ....................................... 58
  4.2 Material Characterization ........................................... 68
  4.3 Prototype Z ............................................................. 72

5 Contribution and Conclusion ........................................... 75
## List of Figures

1.1 Artist rendition of Explorer-1, NASA ........................................ 3

2.1 (a) Monopole at 250 MHz, (b) Radiation pattern of the monopole [2] 8

2.2 (a) Monopole with reflecting plane, (b) 2D Radiation pattern of the monopole. [3] .................................................. 9

2.3 Gain vs Frequency for helical antennas [5] ................................. 10

2.4 (a) Deployable Helical antenna (b) Simulated Deployment [6] ...... 11

2.5 (a) Directive gain plotted against $\theta$ (b) Axial ratio as a function of frequency [6] .................................................. 12

2.6 (a) Directive gain plotted against $\theta$ (b) Axial ratio as a function of frequency [6] .................................................. 13

2.7 (a) Conical log spiral antenna for CubeSats(b) Radiation Pattern for the CLSA. [6] .................................................. 15

3.1 Circular Waveguide geometry. .................................................. 20

3.2 Conical Horn antenna [5] .................................................. 22

3.3 Gain as a function of aperture diameter and axial length [8] ....... 23
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.4</td>
<td>Radiation characteristics of conical horn a-f (after A.P.King [8])</td>
<td>25</td>
</tr>
<tr>
<td>3.6</td>
<td>Ridge arms separated by a gap to create the slot, one end is shorted with the help of a bridge.</td>
<td>33</td>
</tr>
<tr>
<td>3.7</td>
<td>Γ for the slot.</td>
<td>34</td>
</tr>
<tr>
<td>3.8</td>
<td>An understanding of the slot functionality.</td>
<td>35</td>
</tr>
<tr>
<td>3.9</td>
<td>Equivalent Circuit for the Slot</td>
<td>36</td>
</tr>
<tr>
<td>3.10</td>
<td>Aerial expansion law [12].</td>
<td>37</td>
</tr>
<tr>
<td>3.11</td>
<td>Exponentially curved ridges of the slot.</td>
<td>38</td>
</tr>
<tr>
<td>3.12</td>
<td>Γ for the exponential ridge.</td>
<td>39</td>
</tr>
<tr>
<td>3.13</td>
<td>Bottom slot to decrease shunt inductance for lower frequencies.</td>
<td>40</td>
</tr>
<tr>
<td>3.14</td>
<td>Reflection Co-efficient Waveguide-fed Conical Horn antenna</td>
<td>40</td>
</tr>
<tr>
<td>3.15</td>
<td>Ridge cross-over.</td>
<td>41</td>
</tr>
<tr>
<td>3.16</td>
<td>Integrated Quad-ridge structure.</td>
<td>42</td>
</tr>
<tr>
<td>3.17</td>
<td>Simulated S-Parameters on CST microwave studio</td>
<td>43</td>
</tr>
<tr>
<td>3.18</td>
<td>Combined Reflection co-efficient.</td>
<td>44</td>
</tr>
<tr>
<td>3.19</td>
<td>Maximum gain plotted as a function of frequency.</td>
<td>44</td>
</tr>
<tr>
<td>3.20</td>
<td>Angular 3dB beamwidth for a constant φ = 0°.</td>
<td>45</td>
</tr>
<tr>
<td>3.21</td>
<td>(a) Radiation Pattern 2GHz, 3GHz, and 4GHz. (b) Radiation Pattern 5GHz,6GHz and 7GHz.</td>
<td>46</td>
</tr>
</tbody>
</table>
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.22</td>
<td>(a) Radiation Pattern 8GHz, 9GHz, and 10GHz. (b) Radiation Pattern 11GHz, 12GHz, and 13GHz.</td>
<td>47</td>
</tr>
<tr>
<td>3.23</td>
<td>Axial Ratio in dB at boresight $\theta = 0^\circ$ for constant $\phi = 90^\circ$.</td>
<td>48</td>
</tr>
<tr>
<td>3.24</td>
<td>Axial Ratio $&lt; 3dB$ around boresight in degrees.</td>
<td>48</td>
</tr>
<tr>
<td>3.25</td>
<td>Ridge-fed Conical Horn antenna.</td>
<td>50</td>
</tr>
<tr>
<td>3.26</td>
<td>Reflection Co-efficient Ridge-fed Conical Horn antenna.</td>
<td>51</td>
</tr>
<tr>
<td>3.27</td>
<td>Gain of the Ridge-fed Conical Horn antenna compared with the gain of the Quad-ridge and plotted against frequency.</td>
<td>51</td>
</tr>
<tr>
<td>3.28</td>
<td>Angular 3dB beamwidth of the Ridge-fed Conical Horn antenna compared with the Quad-ridged and plotted against frequency.</td>
<td>52</td>
</tr>
<tr>
<td>3.29</td>
<td>Axial Ratio in dB at boresight of the Ridge-fed Conical Horn antenna compared with the Quad-ridged and plotted against frequency.</td>
<td>53</td>
</tr>
<tr>
<td>3.30</td>
<td>(a) Radiation Pattern 2GHz, 3GHz, and 4GHz. (b) Radiation Pattern 5GHz, 6GHz, and 7GHz.</td>
<td>54</td>
</tr>
<tr>
<td>3.31</td>
<td>(a) Radiation Pattern 8GHz, 9GHz, and 10GHz. (b) Radiation Pattern 11GHz, 12GHz, and 13GHz.</td>
<td>54</td>
</tr>
<tr>
<td>4.1</td>
<td>Fabricated fin</td>
<td>57</td>
</tr>
<tr>
<td>4.2</td>
<td>(a) Feed slot milled on the fin side (b) Inserted coax which turns into a probe and feeds the ridge.</td>
<td>58</td>
</tr>
<tr>
<td>4.3</td>
<td>S-parameter measurement set up for the fabricated quad-ridge.</td>
<td>59</td>
</tr>
<tr>
<td>4.4</td>
<td>$\Gamma$ comparison between measured and simulated for 50\Omega.</td>
<td>60</td>
</tr>
</tbody>
</table>
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5</td>
<td>(a) 2GHz Horizontal radiation pattern. (b) 2GHz Vertical radiation</td>
<td>62</td>
</tr>
<tr>
<td>4.6</td>
<td>(a) 3GHz Horizontal radiation pattern. (b) 3GHz Vertical radiation</td>
<td>62</td>
</tr>
<tr>
<td>4.7</td>
<td>(a) 4GHz Horizontal radiation pattern. (b) 4GHz Vertical radiation</td>
<td>63</td>
</tr>
<tr>
<td>4.8</td>
<td>(a) 5GHz Horizontal radiation pattern. (b) 5GHz Vertical radiation</td>
<td>63</td>
</tr>
<tr>
<td>4.9</td>
<td>(a) 6GHz Horizontal radiation pattern. (b) 6GHz Vertical radiation</td>
<td>64</td>
</tr>
<tr>
<td>4.10</td>
<td>(a) 7GHz Horizontal radiation pattern. (b) 7GHz Vertical radiation</td>
<td>64</td>
</tr>
<tr>
<td>4.11</td>
<td>(a) 8GHz Horizontal radiation pattern. (b) 8GHz Vertical radiation</td>
<td>65</td>
</tr>
<tr>
<td>4.12</td>
<td>(a) 9GHz Horizontal radiation pattern. (b) 9GHz Vertical radiation</td>
<td>65</td>
</tr>
<tr>
<td>4.13</td>
<td>(a) 10GHz Horizontal radiation pattern. (b) 10GHz Vertical radiation</td>
<td>66</td>
</tr>
<tr>
<td>4.14</td>
<td>(a) 11GHz Horizontal radiation pattern. (b) 11GHz Vertical radiation</td>
<td>66</td>
</tr>
<tr>
<td>4.15</td>
<td>(a) 12GHz Horizontal radiation pattern. (b) 12GHz Vertical radiation</td>
<td>67</td>
</tr>
<tr>
<td>4.16</td>
<td>(a) 13GHz Horizontal radiation pattern. (b) 13GHz Vertical radiation</td>
<td>67</td>
</tr>
</tbody>
</table>
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.17</td>
<td>Legends for the materials</td>
<td>68</td>
</tr>
<tr>
<td>4.18</td>
<td>(a) Substrate 1. (b) Substrate 2.</td>
<td>69</td>
</tr>
<tr>
<td>4.19</td>
<td>(a) Substrate 3 (b) Substrate 4.</td>
<td>70</td>
</tr>
<tr>
<td>4.20</td>
<td>(a) Substrate 5 (b) Substrate 6.</td>
<td>70</td>
</tr>
<tr>
<td>4.21</td>
<td>(a) Ridges shaped on foam and mesh. (b) Foam surface treated with conductive epoxy to treat the mesh.</td>
<td>72</td>
</tr>
<tr>
<td>4.22</td>
<td>The bounded ridge edge</td>
<td>73</td>
</tr>
<tr>
<td>4.23</td>
<td>Prototype Z.</td>
<td>73</td>
</tr>
<tr>
<td>4.24</td>
<td>Measured reflection co-efficient</td>
<td>74</td>
</tr>
</tbody>
</table>
# List of Tables

1.1 Classification of Satellites ........................................... 2

2.1 Classification of Helical Antennas ................................. 10

3.1 Values of $p'_{nm}$ for TE modes of a Circular Waveguide .... 21

3.2 Conical Horn configurations a-f as measured by Gray and Schelkunoff with the optimum diameters for the respective axial length. .... 24

3.3 Antenna characterization with respect to direction of max radiation, Realized gain in the direction of maximum radiation and 3dB Beamwidth ......................................................... 46

4.1 Measured and Simulated gain results. ............................. 61

4.2 Conductivity of the six substrates. ................................. 71
Chapter 1

Introduction

1.1 Overview

Outer Space has aroused curiosity and garnered respect of human species since the dawn of civilization. From worshipping the sun and other celestial constellations and the geocentric model of the universe to unmanned mission on the Mars and 'The Voyager' leaving the solar system, man has come a long way in it’s quest for knowledge about the extra-terrestrial.

In 1957, Sputnik1 the first man made satellite was launched into LEO (lower earth orbit) which gave us vital information about the ionosphere and opened the gates for what would the most informative period about outer space for human species. Sputnik1 was a metal sphere shaped object 58 cm in diameter and attached to four monopole antenna structures between 2.4m to 2.9m in length to relay the information to base stations at Earth, with the two dominant frequencies used being 20.002MHz and 40.002 MHz. Since then, man has made numerous successful and unsuccessful satellite launches capable of carrying out a variety of missions. The
evolution of satellites saw them getting bigger and bulkier capable of generating and handling significantly higher power for multifunctional payloads capable of delivering a much better RF performance in terms of EIRP, G/T and spatial and polarization isolation [1]. The conventional satellites are typically used for fixed satellite services (FSS), broadcasting satellite services (BSS) and broadband services requiring power supply of up to 15kW [1]. The integration and launch of a conventional satellite costs anything from a few hundred million to billions of US dollars, which has been a potential deterrent to putting satellites into orbit.

<table>
<thead>
<tr>
<th>Type of Satellite</th>
<th>Mass(Kg)</th>
<th>Cost(US dollars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional Large-satellites</td>
<td>&gt; 1000</td>
<td>0.2 – 2 Billion</td>
</tr>
<tr>
<td>Medium-satellites</td>
<td>500 – 1000</td>
<td>50 – 100M</td>
</tr>
<tr>
<td>Mini-satellites</td>
<td>100 – 500</td>
<td>10 – 50M</td>
</tr>
<tr>
<td>Micro-satellites</td>
<td>10 – 100</td>
<td>2 – 10M</td>
</tr>
<tr>
<td>Nano-satellites</td>
<td>1 – 10</td>
<td>0.2 – 2M</td>
</tr>
<tr>
<td>Pico-satellites</td>
<td>&gt; 1</td>
<td>20 – 200K</td>
</tr>
<tr>
<td>Femto-satellites</td>
<td>&gt; 0.1</td>
<td>0.1 – 20K</td>
</tr>
</tbody>
</table>

Table 1.1: Classification of Satellites

The advancement in DSP (Digital Signal Processing) and VLSI (Very Large Scale Integration) has turned the tide of evolution of satellites and now small satellites are gaining notable popularity as they exist along with advanced circuits of low mass and power consumption to carry out complex space applications [1]. The low cost and quick turn around time of such capable small satellites has revolutionized the satellite industry, particularly space research. Several Universities initiated small satellite programs to progress the technology and applications of such small satellites to astonishing heights. Small satellites can be classified into several categories depending on their physical size, cost of manufacture and turn around time. The generalized form of such a classification is detailed in Table 1.1 [1].
Chapter 1. Introduction

CubeSat a nomenclature originating from its shape of a cube is a type of nano-satellite with a mass of less than 1.33Kg and shaped $10cm \times 10cm \times 10cm$ (1U) making the volume of the satellite exactly equal to 1L. The concept of a CubeSat was conceived by Professor Jordi Puig-Suari of California Polytechnic State University and Professor Bob Twiggs of Stanford University in 1999. The first Cubesat was launched from Russia in 2003 when four CubeSats were put into orbit including the QuakeSat of USA. By 2012 there were 75 cubesats on orbit which speaks of the volume of popularity of nano-satellites as a form of Space research. Small satellites can cater to various applications from telemetry and tracking to space weather monitors, space telescopes and relaying information from distant satellites. The operational frequency determines the microwave components and the digital processing system. Depending on the mission characteristics the satellite may have one or multiple antennas to cater to the satellite and the load which might require faster data rates for it’s applications. The preferred antenna choice for a CubeSat platform has been monopoles/dipoles or an array of wire antennas. Such antennas can be arranged in a manner to achieve circular polarization and a high gain. Their popularity is
Chapter 1. Introduction

driven by the simplicity of their design and deployment mechanisms. Also their omni-directional radiation pattern plays a vital role in tracking application. For more sophisticated applications payload specific high gain, wideband deployable antennas are employed for high speed downlinks. The Log Periodic Crossed Dipole array which exhibits a wide bandwidth, a narrower beamwidth and higher gain has found popularity among small satellites. However, LPCD presents more complexity in deployment mechanisms compared to a dipole. Different forms of deployable helical antennas has found wide spread applications in Cubesats and other small satellites due to it’s circular polarization and capability of operating in UHF and VHF frequency bands. Other applied antennas include patch excited cup antennas, patch arrays and other antennas printed on substrates which can be mounted on one of the side walls and does not require a deploying mechanism.

The advancement in technology is pushing the capabilities of small satellites beyond the realm of thinking of the time when Sputnik1 was launched. Antenna engineers are required to come up with innovative solutions to achieve deployable designs for high performance antennas as this has been a bottleneck for high speed downlinks, a quintessential factor in the evolution of small satellites.

1.2 Motivation for Ridge-fed Conical Horn

Antenna requirements on small satellites has evolved over the last decade to several applications that require high data transfer rates as discussed briefly in the preceding section. The information exchange rate or simply put the data rate in a link is governed by the Shannon Heartley Theorem which defines the highest bound on the
Chapter 1. Introduction

information exchange rate or Channel Capacity $C$ in bits/second as,

$$C = \frac{1}{2} \log_2 (1 + \frac{S}{N}) \quad (1.1)$$

Where,

$C =$ Channel Capacity in bits/second (bps).

$B =$ Bandwidth of the channel in Hertz.

$S =$ Average received signal power over the bandwidth in Watts.

$N =$ Additive white Gaussian noise in Watts.

Shannon Hartley theorem in equation 1.1 proves the direct proportionality of the data rate to bandwidth and gain parameters of the antenna associated with the link. Bandwidth and power level reflected in the gain figures therefore acts as the bottlenecks and sets the theoretical upper limits of data transfer for the satellite payload. Wideband antennas are difficult to design, achieving wideband impedance matching and maintaining a good radiation efficiency over the spectrum at the same time presents a collage of intriguing puzzles for the engineers. For effective outer space applications the antenna needs to be circularly polarized as well apart from presenting a wideband impedance bandwidth and drive significantly high gain figures. The constraints to a realistic deployment needs to be maneuvered for a viable deployable design.

In this thesis we propose a wideband antenna spanning more than a decade of GHz in frequency bandwidth and has a gain equal to or higher than 10dB over the entire spectrum with circular polarization and a potentially wide beamwidth.
Chapter 1. Introduction

1.3 Thesis Contribution

The topic of this study has been to explore the possible antenna options for small satellites. Conceptualize and design a Conical Horn antenna spanning a frequency spectrum from 2Ghz to 13 GHz which is robust and can be made to deploy from a small satellite platform once in orbit, yet maintaining the stellar performance characteristics of a conventional circularly polarized horn antenna.

The thesis will start with a brief history of the antennas implemented on a small satellite platform so far. A brief analysis of the performance of the designs implemented is presented. The flow moves on to the primary goal of the thesis, designing the antennas and its wideband functionality that can be successfully deployed from a CubeSat platform with enough gain to satiate the link budget and the design mechanism to make the antenna circularly polarized. Designing an antenna with such strict constraints is all about trade offs between parameters and optimization to find the best possible solution. The hurdles faced during designing process are discussed.

A new substrate is developed by the California Institute of Technology and is investigated and characterized in this thesis as a possible solution for a deployable design. Finally different prototypes are developed using different substrates as antenna materials. The fabricated prototypes are characterized and compared to the simulated results. Explanations will be provided for all the trade offs to encourage intuitive insights as to how to achieve the best possible configuration for such design requirements.
Chapter 2

Background: Previous Research

The preferred antenna choice for small satellite platform has been monopoles/dipoles or an array of wire antennas. Their popularity is driven by the simplicity of their design and deployment mechanisms. The omnidirectional pattern of such an antenna makes it a preferred choice for tracking and satellite command applications. But these antennas are narrow band antennas with moderate gain which limits their data transfer rate to a mere minimum. Depending on the payload application more often than not small satellites use multiple antennas as stated earlier. The application specific antennas need to be high gain, wideband antennas to increase data rates. But the gain of an antenna is usually directly proportional to it’s physical size and hence these antenna structures tend to be large and bulky with respect to the satellite platform and needs to be deployed. Scientists and engineers have experimented with a variety of antenna structures to conceptualize and implement deployable structures to achieve the best possible performance. In the following sections we will look at the various antennas implemented on small satellites specifically CubeSats.
2.1 Dipoles/Monopoles

Monopoles, Dipoles or an array of monopole or dipole antennas have been the choice for small satellite platforms. A valid rationale for this choice can be attributed to their simple design process and deployment mechanism.

The dipole or monopole over a ground plane has an omni-directional radiation pattern which makes it a perfect candidate for satellite bus traffic. Such antennas have found widespread acceptance when it comes to small satellites [1] [2]. Various techniques have been introduced to make these whip like structures deployable. Constantine et al designed a monopole operating at 250MHz which uses bistable composite tape-spring to stow and subsequently deploy the structure once on orbit shown in figure 2.1 [2]. The monopole exhibits doughnut shaped omnidirectional radiation pattern and drives a gain of 2.18 dBi, similar to that of a dipole. An array of such monopoles or using multiple reflecting planes can drive a higher gain [2] [3].

The shapes and sizes of different possible reflecting plane configurations are studied in [3]. The results show significant improvement in gain figures for various CubeSat configurations. A 3U reflecting plane designed for a 3U CubeSat shows a gain
of 7.95dBi and a HPBW of 90° for a quarter-wave monopole operating at 2.3GHz positioned at the center of one of the plates shown in figure 2.2. Several other configurations varying in realized gain and HPBW can be referenced at [3].

2.2 Helical Antennas

The family of helical antennas is second to mono/dipole antennas when it comes to antenna alternatives for small satellites. The helical antenna is a traveling wave antenna with one or many conducting/radiating elements wound into the shape of helix [4][5]. Depending on the number of conducting elements the family of helical antennas is classified in Table 2.1.
Chapter 2. Background: Previous Research

<table>
<thead>
<tr>
<th>Type of Helical antenna</th>
<th>Number of coils</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helical</td>
<td>1</td>
</tr>
<tr>
<td>Bifilar</td>
<td>2</td>
</tr>
<tr>
<td>Quadrifilar</td>
<td>4</td>
</tr>
<tr>
<td>Multifilar</td>
<td>&gt; 4</td>
</tr>
</tbody>
</table>

Table 2.1: Classification of Helical Antennas

This type of antennas can be designed for high gain and improved beamwidth by carefully optimizing the number of turns. The spring like structure makes helical antennas a good candidate for deployment mechanism since springs have an inherent

Figure 2.3: Gain vs Frequency for helical antennas
deployment mechanism in itself by the virtue of it’s shape.

The spring like structure makes helical antennas a good candidate for deployment mechanism since springs have an inherent deployment mechanism in itself by the virtue of it’s shape. The axial ratio of helices is directly related to the number of turns in the design by a simple equation given as

\[ AR_{\text{helical antenna}} = \frac{2N + 1}{2N} \]  

where \( N \) is the number of turns of the helical antenna. For a large number of turns the axial ratio approaches unity which generates perfectly circular polarized waves. The single coil helical antenna can generate anything between 6.5dBi to 18 dBi of gain depending on it’s design parameters as shown in figure 2.3. The wide bandwidth, circular polarization and capability of driving a higher gain explains why helical antennas have been such a popular choice for space communications.

Ochoa et al came up with an innovative ultra-compact mechanical design (300:1 volume ratio) for a 5 turn helical antenna which can be scaled to required applications
Chapter 2. Background: Previous Research

Figure 2.5: (a) Directive gain plotted against $\theta$ (b) Axial ratio as a function of frequency [6]

for future nano and micro satellites that can be deployed from a CubeSat platform operating between 230MHz and 400MHz [6]. PEEK thermoplastic pultruded tape strips .010-inch thick, .625-inch wide is used as a substrate and 3.5 mil conductive copper tape as the RF conductor for their design.

The antenna in figure 2.4 is 54.33 inches (137.9982 cm) in length and 14.5 inches (36.83 cm) in diameter in its deployed state and can be rolled and coiled into a volume of approximately 0.5U [6]. The antenna drives a gain of 4dBi-13dBi over the frequency spectrum and exhibits an axial ratio of less than 2.0dB.

The directive gain (dBi) of the antenna is plotted against $\theta$ degrees in the radiating plane in figure 2.5(a). The boresight axial ratio as a function of frequency is shown in figure 2.5(b). The antenna drives significant gain and is circularly polarized
Chapter 2. Background: Previous Research

which makes it an excellent choice for small satellite platforms.

2.3 Log Periodic Dipole Array

The Log periodic dipole array or the LPDA is a multielement, wideband, directional antenna. The LPDA is a combination of a series of dipole elements gradually increasing in length away from the direction of max radiation. The antenna is typically associated with gain figures between 7dBi and 12dBi over it’s frequency bandwidth [1]. The geometrical configuration of the design is crucial and determines it’s operation and is defined by the inverse of the geometric ratio $\tau$.

![Figure 2.6: (a) Directive gain plotted against theta (b) Axial ratio as a function of frequency [6]](image)

$$\frac{1}{\tau} = \frac{l_2}{l_1} = \frac{l_n}{l_{n+1}} = \frac{R_2}{R_1} = \frac{R_{n+1}}{R_n} = \frac{d_2}{d_1} = \frac{d_{n+1}}{d_n} = \frac{s_2}{s_1} = \frac{s_{n+1}}{s_n}$$  \hspace{1cm} (2.2)

where,

$\tau =$ geometric ratio.
Chapter 2. Background: Previous Research

l= length of elements.
R= spacing between the elements.
d= diameter of the elements.
s= gap at the dipole centers.

The bandwidth varies between $\lambda/2$ of the longest element at the lower end to $\lambda/2$ of the smallest element as the highest operating frequency. The antenna achieves good gain while maintaining a beamwidth as given figure 2.6(b). The physical size and the involvement of many elements makes the deployment mechanism challenging but it is considered as a potential candidate and work has been ongoing to study the viability of LPDA or LPCDA as a possible antenna choice. [2].

2.4 Conical log spiral

The Conical log spiral antenna or the CLSA has been proved to be another worthy alternative for small satellite platforms. It is basically a spiral antenna on a conical structure to reduce back lobes and increase gain. This type of antennas can be designed to achieve a potential bandwidth of 150% if designed properly. The Conical log spiral can have more than one arms and fed with proper phase difference produces perfectly circularly polarized waves. The usual problem associated with these types of antenna is the physical size which can be a constraint. A bottom-fed conical log spiral antenna designed to deploy from a CubeSat platform is shown is figure 2.7 [7]. The antenna exhibits a directional beam and good gain and it is fed from the bottom which makes it suitable to deploy. It also exhibits a circular polarization over a wide beamwidth [7].

The constant need for more bandwidth and a higher gain is the driving factor for
Chapter 2. Background: Previous Research

Figure 2.7: (a) Conical log spiral antenna for CubeSats (b) Radiation Pattern for the CLSA. [6]

this thesis. The antenna concepts implemented and the design is presented in the next section.
Chapter 3

Antenna Concept and Design

CubeSat antenna applications have evolved in the last decade from telemetry, tracking and attitude control to high speed links for data transfer to cater for much more sophisticated applications such as space weather monitors and space telescopes. The more sophisticated applications like images require a high speed link for the data. A high speed link is defined by a higher bit rate which in turn is directly proportional to the bandwidth and gain of the antenna. In other words, in order to achieve a high speed down-link the antenna needs to present a wide bandwidth and drive a higher gain. The primary focus of this thesis is to develop a high gain wideband antenna solution capable of deploying from a CubeSat platform.

Mechanical engineers at AFRL (Air Force Research Limited) and Caltech (California Institute of Technology) came up with a mechanical solution that would enable a conical horn flare to be folded inside a 6-U CubeSat and deploy once in orbit. The antenna is conceived to be composed of very light weight and stiff material capable of deploying autonomously yet maintaining the characteristics of a horn antenna. This development would mean the most reliable family of antennas can now be used as
antenna alternatives for small satellites. Horn antennas are synonymous with high
directivity, and since there is limited loss the directivity often matches it’s gain fig-
ures. We will look at the initial concepts of a horn antenna in brief and design an
antenna keeping in mind the features needed for successful deployment.

3.1 Horn Antenna

Sir Oliver Lodge demonstrated the use of the applications of waveguides as transmis-
sion lines. Only a few years later in 1897 Sir Jagadish Chandra Bose in his pioneering
experiments demonstrated the first applications of a horn antenna. Horn antennas
by the virtue of it’s inherent structure makes the transition between the transmis-
sion line and free space for EM waves. It has found widespread applications owing
to it’s directive property and the ability to drive a consistent high gain over a large
bandwidth. Common applications of this type of antennas include communication
systems, electromagnetic sensing, biomedical purposes, feeding elements for reflector
antennas and satellite communications to name a few [5]. Horn antennas come in
various sizes and shapes which determine their operational capabilities and hence
their applications. The two most widely used horn antennas would be the rectangu-
lar pyramidal horn and the conical horn antenna.

The general feeding mechanism for horn antennas is by a waveguide suitable for
the horn. For example a rectangular pyramidal horn antenna is fed with a rectangu-
lar waveguide designed for the cut-off frequencies as required and a conical horn is
fed by a circular waveguide to perfectly match at the waveguide/flare aperture. The
input matching for a horn antenna is determined based on two set of criteria (a) The
matching between the waveguide and the horn flare and (b) the matching between
the flare aperture and the free space of the medium in which the radiated field is
propagating. The two criteria combined can produce a highly oscillatory return loss over a frequency band. However, the transition from the waveguide to the flare contributes the major share to the overall reflection coefficient of the horn antenna as the reflections from the aperture to the free space is generally much less [5].

One end of a waveguide is usually shorted with a metallic plate and excitation inside a waveguide generates the travelling waves which travels along the length of waveguide and hits free space which acts as a barrier for the EM waves much like land does to sea waves. The waves impinges on this barrier and is reflected back inside the waveguide resulting in standing waves and no radiation. The waveguide is thus flared to achieve an impedance match and facilitate smooth transition creating the horn antenna. The fields inside the flare change from a plane wavefront to a curved wavefront which is highly desirable for radiation [5]. Mathematical and experimental formulations already exist which can calculate the radiated fields to a fair degree of accuracy given the horn aperture (the surface area across horn opening). The aperture field is approximated by the transverse electric field of the propagating mode as it would present itself in a waveguide of the size and shape of the horn aperture. This presents an interesting dilemma, since the size of flare increases linearly over distance the boundary conditions suggests the existence of higher order modes inside flare which causes anomalies between the calculated fields and the measured fields. However, the flare angle is generally considered small enough and the higher order fields are neglected as a first principle assumption [5].

The rectangular pyramidal horn is by far the most widely used horn antenna and the most studied and postulated. This antenna also presents the designer with independent control over it’s beamwidth in two principal planes of radiation by controlling the length and the width of the rectangle. A special case of pyramidal
Chapter 3. Antenna Concept and Design

horn is a sectoral horn which is flared in only one plane to create fan shaped beams, broad in the plane orthogonal to the flare\[5\]. Non-linear flares have also been designed to improve beamwidth and minimize side lobes. Corrugations have been implemented to improve cross-polarized radiation. The rectangular pyramidal horn antenna is multi-faceted antenna and is extremely intriguing from a designers point of view, but for this thesis a different antenna was chosen.

3.2 Conical Horn Theory

The Conical horn antenna is a conical structure with a circular geometry. The cone can be conceived as two circles placed a distance apart and lofted along it’s revolving axis, the loft can be linear or exponential depending on the application and design. Such a structure is often used in loudspeakers to guide acoustic waves, the working principal for guiding the waves is similar for both. The structure of this antenna is perhaps one of the simplest yet effective structures. The gain of the antenna is directly proportional to the axial length and hence, the antenna can be infinitely long to drive a infinite gain. The conical horn was studied in details by A.P.King as early as 1950. In his publication for the Proceeding of IRE in 1950 he detailed the correlation between the antenna gain and the antenna dimensions \[8\].

Conical horns and circular waveguide feeds are studied next to get an idea of the working principle of such a structure. Then the standard conical horn will be modified and new features added to make it suitable for a realistic deployment mechanism.
3.2.1 Circular Waveguide

The conical horn is usually fed with a circular waveguide. The geometry of such a waveguide with a radius 'a' is shown in figure 3.1. The circular waveguide supports TE and TM but not TEM since it is just a hollow cylinder made up of a single conductor which constitutes the side walls of the guide. The dominant and the most widely used mode of a circular waveguide is the $TE_{11}$ mode. The propagating TE modes are defined by the cut-off wave number $k_{c_{nm}}$.

$$k_{c_{nm}} = \frac{p'_{nm}}{a}$$

where,

- $k_{c_{nm}}$ = wave number.
- $n$ = number of circumferential ($\phi$) variations.
- $m$ = number of radial ($\rho$) variations.
Chapter 3. Antenna Concept and Design

The Propagation constant of the $TE_{nm}$ mode is given by

$$\beta_{nm} = \sqrt{k^2 - k_c^2} = \sqrt{k^2 - \left(\frac{p'_{nm}}{a}\right)^2}$$  \hspace{1cm} (3.2)$$

The values of $p'_{nm}$ are tabulated below to deduce the TE modes as and when they propagate. The $TE_{11}$ is clearly the dominant mode followed by $TM_{01}$ and $TE_{21}$ and so on $[9]$. The cut-off frequency for each mode is given by

$$f_{c_{nm}} = \frac{k_c}{2\pi\sqrt{\mu\epsilon}} = \frac{p'_{nm}}{2\pi a\sqrt{\mu\epsilon}}$$  \hspace{1cm} (3.3)$$

Hence, the waveguide is designed according to the operating frequency band and excited to feed the horn. The radiated fields of a circular waveguide is given by equation 3.4 and 3.5 $[5]$.

$$E_\theta(r, \theta, \phi) = 2\pi a \frac{e^{-jkr}}{r} J_1(k_c a) \frac{J_1(wa)}{k_c wa} \cos\phi$$  \hspace{1cm} (3.4)$$

$$E_\theta(r, \theta, \phi) = 2\pi a \frac{e^{-jkr}}{r} J_1(k_c a) \frac{k_c J'_1(wa)}{k^2 - w^2} \cos\theta \sin\phi$$  \hspace{1cm} (3.5)$$

where,

a= aperture radius.
w= k sin$\theta$.
k_c a = 1.841181.
J_n = Bessel function of the order n.
Chapter 3. Antenna Concept and Design

3.2.2 Conical Horn Flare

The circular waveguide feed of the previous section is aperture matched at the junction between the flare and the guide to facilitate a smooth impedance transformation. The radiation characteristics of a typical conical horn is found in equations 3.6 and 3.7 after the work done by Narasimhan and Rao [5]. The equations are found to accurately predict radiation patterns for long horn antennas \((L > 5\lambda)\) and semi cone angles less than 35°.

\[
E_{\theta}(r, \theta, \phi) = \frac{jE_0 k a^2}{2} \frac{e^{-jkr}}{r} (G_0(w) - G_2(w)) \cos \phi \tag{3.6}
\]

\[
E_{\phi}(r, \theta, \phi) = -\frac{jE_0 k a^2}{2} \frac{e^{-jkr}}{r} \cos \theta (G_0(w) + G_2(w)) \sin \phi \tag{3.7}
\]
where,
\[ G_m(w) = \frac{1}{a^2} \int_0^a J_m(p'_nm\rho'/a)J_m(w\rho') \exp(-jk\rho'^2/2L) \rho' d\rho' \]

\[ p'_nm = \text{Value can be referenced from Table 3.1.} \]

\[ w = ks\sin\theta. \]

Figure 3.3: Gain as a function of aperture diameter and axial length

A.P.King postulated, a conical horn with a fixed axial length exhibits a varied...
gain which is proportional to the diameter of the horn \[8\]. The gain of the fixed
length antenna is found to increase with increasing diameter up to a certain point or
the 'optimum value', after which it becomes an inverse correlation, i.e as the diameter
\((d_m \text{ or } 2a)\) increases the gain decreases. The diameter when kept constant the gain is
found to be directly proportional to the axial length of the antenna, in other words
an infinitely large antenna will theoretically exhibit infinite gain.

M.C.Gray and S.A.Schelkunoff performed numerous numerical and experimental
calculations and derived the correlation plot in Figure 3.3 where \(L\) is the axial length
and the diameter is denoted by \(d_m\). The Y axis of the plot is the absolute gain
achievable and the X axis is the diameter/operating wavelength. The plot calculates
the optimum value of diameter for a given axial length or vice-verse. The values of
6 measured conical horns are plotted alongside the correlation marked from a-f. The
optimum value for increasing diameter and axial length is plotted with a dotted line
and is increasing with increasing aperture diameter and axial length. Configurations
a and b were chosen to be less than the optimum value, c was chosen to be very close
to and d-f were greater than the optimum value. The values of a-f configurations are
tabulated in table 3.2 with the optimum values of diameter for the respective axial

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Fixed Axial Length (L)</th>
<th>Diameter (2a)</th>
<th>Optimum Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>8(\lambda)</td>
<td>1.4(\lambda)</td>
<td>4(\lambda)</td>
</tr>
<tr>
<td>b</td>
<td>3.5(\lambda)</td>
<td>2.6(\lambda)</td>
<td>3(\lambda)</td>
</tr>
<tr>
<td>c</td>
<td>3.9(\lambda)</td>
<td>3.6(\lambda)</td>
<td>3.6(\lambda)</td>
</tr>
<tr>
<td>d</td>
<td>3.1(\lambda)</td>
<td>3.6(\lambda)</td>
<td>3.1(\lambda)</td>
</tr>
<tr>
<td>e</td>
<td>2.4(\lambda)</td>
<td>3.6(\lambda)</td>
<td>2.8(\lambda)</td>
</tr>
<tr>
<td>f</td>
<td>2.8(\lambda)</td>
<td>4.1(\lambda)</td>
<td>3(\lambda)</td>
</tr>
</tbody>
</table>

Table 3.2: Conical Horn configurations a-f as measured by Gray and Schelkunoff
with the optimum diameters for the respective axial length.
length to assess the degree of accuracy and reliability of gain vs parametric plots of figure 3.3. The best possible configuration was c and is found to exhibit a gain of 18$dBi$, close to the max of the arc that defines the optimum value for a cone with a fixed axial length 3.9\(\lambda\). The aperture diameter for a and b was chosen to be smaller than their respective optimum values for the respective axial length, the measured values fall to the left of the arc, while diameters for configurations d-f were chosen to be greater than the optimum value and the measured values fall to the right of the arc which goes well with the theory. The greater the difference with the optimum

![Figure 3.4: Radiation characteristics of conical horn a-f (after A.P.King)](image)
value the farther the measured data falls on the plot, or in other words the greater the diameter deviates from the optimum value the lesser gain it achieves.

The radiation patterns for the 6 configurations of conical horns are plotted in figure 3.4. The observation of these plots give decisive insights for a designer. The magnetic plane always presents one main lobe and no minor lobes irrespective of it’s aperture diameter and axial length. The electric plane however has distinct major and minor lobes. The major lobe is prominent and separated from the minor lobe when the aperture diameter is much smaller than the optimum value. As the aperture diameter approaches the optimum value, the main lobe and the minor lobe merges together to form one distinct beam, also given by the fact that the maximum gain is achieved for such configuration. The increment of the aperture diameter with respect to optimum is found to enhance the minor lobe to a point when the minor lobe takes over the major lobe and splits the major lobe into two along the cone revolving axis. The direction of maximum radiation is no longer along the cone revolving axis. The greater the distance in wavelength between the tip of the spherical waveform and the two dimensional horn aperture the greater is the phase error. This is one of the primary challenges faced while designing a horn antenna with a wide frequency band and will be discussed in later sections during design and analysis.

The antenna efficiency incurs losses due to the nonuniform intensity distribution, polarization and phase difference at the horn aperture [5]. The effective area of an antenna is a measure of efficiency realized by the design. For the ideal conical horn antenna with uniform intensity distribution, polarization and phase difference, the effective area is the same as the physical area of the antenna. The effective area of a conical horn antenna is given by equation 3.8 [8]

\[ A_{eff} = \frac{g\lambda^2}{4\pi} \]  

(3.8)
Chapter 3. Antenna Concept and Design

Where,
\[ A_{\text{eff}} \] = Effective area of the antenna.
\[ g \] = Absolute power gain of the antenna.

The effective area is usually referred to as a ratio of the effective area to the actual physical area of the aperture of the antenna. The actual area \( A \) of the antenna is
\[ A = \frac{\pi d_m^2}{4} \]  
(3.9)

and hence the ratio of effective area to physical area of the antenna is given by equation 3.10.
\[ \frac{A_{\text{eff}}}{A} = \frac{g\lambda^2}{\pi^2d_m^2} \]  
(3.10)

King et al found out that for optimally designed horn antennas, the effective area of the horn is 52% of the actual physical area. The effective area increases for increasing axial length and a fixed optimum diameter to 82% for four times the optimum axial length after which it slows down. \( A_{\text{eff}} \) for infinitely long horn is 84%.

The 3dB angular beamwidth of a standard conical horn antenna for electric and magnetic planes \( \theta_E \) and \( \theta_M \) is given by the equations 3.11 and 3.12 respectively [8].

\[ \theta_E = \frac{60}{(d_m/\lambda)} \]  
(3.11)

\[ \theta_M = \frac{70}{(d_m/\lambda)} \]  
(3.12)

The empirical formulas for 3dB beamwidth suggests that the beamwidth in the H-plane is slightly broader than that of the E-plane. It is also inversely proportional
to the $\lambda$ of operation for a fixed diameter and hence, for a fixed diameter the 3dB beamwidth of the conical horn antenna decreases with increasing frequency. This can be a major setback for a wideband conical horn antenna as the beamwidth can not be kept constant. This issue will come up in the following sections as the design and results are discussed.

The theory of the Conical Horn Antenna is discussed in details in this section. However, designing an antenna is a whole new ball game and throws up numerous new challenges for the antenna designer. The upcoming sections will deal with designs and challenges faced during the design. The conventional conical horn antenna modified and innovated to make it robust for small satellite applications.

### 3.3 Conventional Conical Horn Antenna

The conventional conical horn is a waveguide-fed directive with a pencil beam, low loss and high gain antenna. The design process is relatively simple. This type of horn is often used as a feed for communication/satellite dishes and radio telescopes among other communicative applications. It is associated with a gain within 10dBi-20dBi, beamwidth between $10^\circ$-$40^\circ$ and a narrow bandwidth of 1.3 : 1 which is very typical for a conical horn antenna. But it suffers several setbacks when it comes to our application and are discussed in brief in the following sections.

#### 3.3.1 Bandwidth

The circular waveguide section has no upper cut-off frequency. $\Gamma$ guide for t continues to stay well under the stipulated -10dB but if the bandwidth is extended it will
Chapter 3. Antenna Concept and Design

excite other unwanted modes which will cause a major loss of power. The next mode for a circular guide is the $TM_{01}$ mode theoretically gets excited at a few hundred MHz from the cut-off $TE_{11}$. There are ways to suppress these unwanted modes from propagating but it will make the design too complicated and unsuitable for deployment.

An effective way of achieving impedance matched bandwidth for frequency decades is to use ridged waveguides. The ridges create a constriction inside the waveguide separating it into two different waveguide resulting in a big separation between the fundamental and the next higher mode. This technique has been widely used in pyramidal horn antennas, but there exist only a few articles of such implementation on a conical horn antenna.

3.3.2 Polarization

The conventional waveguide-fed conical horn antenna is a linearly polarized antenna. The proposed antenna must be circularly polarized in order to maintain a stable downlink with the ground station as discussed in section 2.1.4. This calls for an implementation of two sets of ridges orthogonal to each other fed with a 90° face shift to facilitate circular polarization. The ridge cross-over needs to be carefully designed to nullify any phase error.

3.3.3 Antenna Material

Copper is the material of preference for horn antenna owing to it’s high conductivity which reduces skin depth. It is also highly malleable and hence easier to mould into the desired shapes. But copper is heavy and can not be made to fold and deploy on
Chapter 3. Antenna Concept and Design

orbit. The antenna needs to be composed of very light and strong material that is capable of folding and deploying autonomously while maintaining the reliability of operation of a Conical horn antenna. This thesis will look into alternative materials for the design along with designing the antenna itself.

3.3.4 Antenna Feed

The feed of the conical horn must be modified in order to make it mechanically robust for deployment once in orbit. The traditional way to feed a ridged horn antenna is to feed the ridge inside a waveguide for both pyramidal and conical horn antennas [5][11][10]. The guide facilitates the transition between the coax and the flared ridge. A circular guide structure creates a problem for the deployment mechanism and hence must be eliminated. In other words the horn antenna must be a single conical structure truncated at the lower edge of the horn flare to facilitate deployment.

This goes against any research work done previously and poses a completely new challenge in addition to other modifications necessary to make a viable antenna design for small satellites such as CubeSats. The information available from the work done so far is taken into account and a probe feed is proposed as shown by [11] [10]. The elimination of the waveguide presents a new dilemma and a new but quintessentially engineering approach is taken in this thesis to solve the puzzle.

3.4 Ridge Design

In 1979, Gibson proposed the Vivaldi or simply a tapered slot antenna as a new member of the class of aperiodic, continuously scaled antenna structure which can have an unlimited bandwidth theoretically [12]. He proved such an antenna structure can
Chapter 3. Antenna Concept and Design

achieve significant gain, linear polarization, low side-lobe levels and instantaneous large frequency bandwidth.

The tapered slot of the design facilitates a travelling wave mechanism of radiation. The energy is strongly bound to the conducting medium at the end where the distance of separation between the two arms is minimum. As the distance of separation increases with respect to the wavelength of the particular frequency, the energy in the travelling wave starts to couple with the radiated field. The flare acts as a perfect medium between the feed at the base of the curvature to free space impedance of 377Ω.

This Vivaldi slot has been characterized over the years and its practical applications are on the rise due to it’s wide impedance bandwidth property. The double-ridged and quad-ridged horn antennas use the same property of the curved ridge surface to achieve decades of frequency in impedance matched bandwidth. Walton and Sundberg were the pioneers of this application [5], designing the first double ridged pyramidal horn antenna, which is cited even today.

Conventionally the conical horn is designed first, allowing the dominant mode to propagate throughout the horn so that it doesn’t get trapped. The ridge is then designed, starting inside the waveguide and rolled off from an optimized point inside the flare. The profile of the ridge is quintessential to operation, generally a $\sin^2$ function or an exponential taper is used. The ridge is fed with a coaxial probe inside the waveguide to facilitate a coax to waveguide transition as shown in figure 3.5 [10]. But for the purpose of this thesis, a coax to waveguide transition has to be eliminated to facilitate the deployment mechanism. A single fin is designed first on CST microwave studio then two identical fins(four ridges) are integrated together to
The design starts with deducing the design dimensions. In section 3.2.2 the realized gain was established as a function of the axial length and the diameter of the conical horn. In absence of our primary radiator the waveguide, the conical structure is shorted at the base with a reflecting plane. The cone dimension is set for the largest wavelength propagating which is 15cm. The length is fixed at 15cm and the corresponding diameter of the horn aperture is chosen to be 170cm, 1.13λ of the lowest frequency. This should yield a 10dB of gain at the lowest frequency and enough leeway to optimize for the smaller wavelengths at higher frequency, so that a gain of 10dB of more can be achieved for the entire frequency band.
Chapter 3. Antenna Concept and Design

The fin (two ridges on one plane constitutes a fin) length is chosen to be equal to the cone length. The modelling of the fins is a challenging task. With the tools available on microwave studio we need to develop ridges for the cone. Two rectangular blocks are placed on XZ plane as shown in figure 3.6 and spaced a distance apart which is parametrized to create a slot of the most primitive form. The bottom of the two ridges is shorted by a bridge. The ridge length along Z is 15cm, ridge breadth along X is chosen such that the two rectangular blocks when added together with the slot width equals the diameter of the aperture.

![Figure 3.6: Ridge arms separated by a gap to create the slot, one end is shorted with the help of a bridge.](image)

The reason for such a parametrization is that there needs to be good connection between the ridges and the cone. The ridges should taper and end at the cone aperture so as to feed the aperture correctly and nullify phase error as much as possible due to spherical wavefront. The thickness or height is 2mm along Y going in and out of the page in figure 3.6. Ideally thicker fins are desirable but our application requires thin fins so that they can be folded and deployed autonomously. The two ridges and the bridge is integrated to form a fin.
The structure now behaves like a slot radiator. The feed point is somewhere above the bridge and towards the bottom so as to allow the exponential curve of the fin. The short at the bottom of the structure is basically acting as a shunt inductance and the large volume of conducting element along Z adds capacitance.

If we can add electric current or voltage in phase we get radiation, nature by itself enables radiation. Let’s see how well the basic slot we made radiates. The structure is fed with discrete port at 3 random position a, b and c spaced 5 mm apart from each other just above bridge along the edge of the slot. The port is swept with respect to two impedance point 50Ω and 75Ω.

![Figure 3.7: Γ for the slot.](image-url)
Chapter 3. Antenna Concept and Design

The results plotted in figure 3.7 are more exciting and intriguing than anyone might think. We see multi-resonances across the frequency spectrum for 50Ω as well as 75Ω. More conducting surface is always good for radiation. So in principle we have an antenna which is acting somewhat like a slot antenna and somewhat like an Inverted F antenna with the slot along the Z axis.

Let’s assume figure 3.8 shows the slot of the figure 3.6, except this slot is shorted on both sides, but let’s undermine that for the sake of understanding what really is going on. Also let’s take the length \( L \) of the antenna to be \( \lambda/2 \) of frequency \( f_0 \). The feed is offset from the center towards the shorted side. Since AB and CD are shorted out, the voltage across them is 0 and peaks at the center. Now, our structure represents a short circuited transmission line, smaller in length on one side than the other. The current will obviously take the shortest path from the higher potential to the lower potential and hence the current will peak at A (and B as they are shorted and height \( H \) is small) and negative at CD. Now, for an antenna to radiate we either need the current to add in phase or the voltage to add in phase. And as we can see to the right of the feed the voltage is adding phase as shown by the big blank arrows.

![Figure 3.8: An understanding of the slot functionality.](image)

We know, impedance \( Z \) is given by,

\[
Z = \frac{V}{I}
\]

\( V=0 \) at A and \( I=0 \) at the center since our slot is \( \lambda/2 \). So impedance at point A will
be

\[ Z = \frac{0}{I} = 0 \]

and the impedance at the center would be,

\[ Z = \frac{V}{0} = \infty \]

Between 0 and \( \infty \) lies all possible values. And that is why when I randomly choose 3 points a, b and c, I get resonances for a certain wavelength where the impedance values of 50\( \Omega \) and 75\( \Omega \) are matched for their respective wavelength.

![Figure 3.9: Equivalent Circuit for the Slot](image)

Let’s look at it from the transmission line point of view, the equivalent circuit for the slot is given by the figure 3.9. The transmission line to the left of the feed is less than \( \lambda/4 \) and acts as an inductor, given by \( L1 \), and that to the right of feed which is then greater than \( \lambda/4 \) acts as a capacitor. Parallel to that we have our radiation resistance \( R1 \). Hence, whenever the inductance and the capacitance are cancelling each other out with respect to wavelength, power is delivered to the load and we have our radiation from the slot. I mentioned something about an Inverted F antenna (IFA), which has a short on one side and open circuit on the other. How does it match to the slot? Well, voltage \( V \) at the center is maximum, which can easily be represented as an open circuit, hence half of a slot is an IFA which actually corresponds well with IFA theory. Our structure has both the mechanism of a slot and an IFA and their resonances may overlap.
So, we have multi resonances but we need a clear bandwidth between 2GHz and 13GHz. We refer to P.J.Gibson, whose curve expansion equation is given by

\[ y = \pm Ae^{px} \]  

(3.13)

Where,

- \( y \): Half separation distance.
- \( x \): Length Parameter.
- \( p \): Magnification factor.

Gibson proposed that when \( x \) is large and positive, the energy is coupled to the field and away from the conducting medium, and is tightly bound to the conductor when \( x \) is small relative to the wavelength of propagation. Now, let’s put his idea to test and see what transpires.

The two edges of the open end of the slot are curved identically. Also, notice that the bridge height has been reduced. The equivalent circuit of figure 3.9 helps to visualize what really happened. The exponential taper has actually reduced the capacitance, which means \( C1 \) has been reduced significantly, hence we increase the slot to the bottom of the feed to adjust the inductance accordingly. Let’s optimize

Figure 3.10: Aerial expansion law
Chapter 3. Antenna Concept and Design

Figure 3.11: Exponentially curved ridges of the slot.

The curvature is simulated with respect to two impedance values of 50Ω and 75Ω. The curvature is also a function of the feed point and hence an optimized curvature for a feed point a, will return losses for another feed point b. The feed point and the curve from Gibson’s equation is optimized. The resonances amalgamate at the higher frequencies and form a clear bandwidth. The feed point is better matched to 75Ω. At this point we can either optimize for 50Ω or 75Ω. Since we already have a good match for over half of our required bandwidth we choose to optimize a 75Ω design.

A careful look at both the plots in figure 3.12 shows that the curvature is only affecting the higher frequencies and not the lower frequencies, the obvious question then would be why? The answer refers back to the equivalent circuit, curvature is essentially reducing capacitance and affecting the higher frequencies. A smooth
transmission at the lower end of the band is still missing. At this point we can opti-
mize the curvature more and truncate the slot with respect to the lower wavelengths 
or we can go back to the transmission line theory and see what really is happening 
to the lower frequencies. The short circuit to the left of the feed is obviously acting 
as an inductor for the larger wavelengths. The inductance is reduced as a next step;

The slot in figure 3.13 is engineered on the shorted side to lower the shunt in-
ductance. The length is optimized for a shorter slot and a longer slot to understand 
the phenomenon. Slot 1 is 25mm and slot 2 is 50 mm in length, keeping in mind the 
length of this particular slot is originally along the breadth of the fin. The results
Chapter 3. Antenna Concept and Design

![Bottom slot to decrease shunt inductance for lower frequencies.](image)

Figure 3.13: Bottom slot to decrease shunt inductance for lower frequencies.

...are plotted in figure 3.14.

The matching at the lower frequencies shows significant improvement. $\Gamma$ has gone up for the higher frequencies, which should be intuitive from the previous discussion.

![Reflection Co-efficient Waveguide-fed Conical Horn antenna](image)

Figure 3.14: Reflection Co-efficient Waveguide-fed Conical Horn antenna
3.5 Quad-ridge Open Boundary

In the last section a single fin was designed which would have worked just fine if our design requirements were a linearly polarized antenna. The antenna needs to be circularly polarized and hence we need two elements orthogonal to each other fed with a 90° phase difference. That would mean the two fins will overlap each other. The two fins should overlap each other right at the center so as to nullify any phase error.

The overlap mechanism is showed in figure 3.15. One fin sits on top of the other by means of a carefully designed slot. The antenna is then placed over a reflecting plane at the bottom to minimize the back lobes and increase the directivity and hence gain of the structure. The reflecting plane also acts as a termination for the conical horn structure once incorporated.

The resulting structure is shown is figure 3.16. The antenna propagates along Z,
which would be in and out of the page. This is an open boundary quad ridged horn, minus the waveguide component. This is an important junction in the development of this design. Now, we have two active elements along XZ and YZ planes intersecting each other. Two ports are set up for the two fins and simulated with a reference impedance of 75Ω.

Figure 3.16: Integrated Quad-ridge structure.

The design is simulated with a high mesh count of $\lambda/20$ on CST. The direction of propagation is along Z. The feeds are set 1mm. The S-parameter results are given in figure 3.17. The difference in the feed position has resulted in two different results for port 1 and port 2. The S11 is below -10dB for both ports which means the $VSWR < 2$ for the entire spectrum. The ports are well matched to the probe feed at 75Ω. The difference between the two feed positions is more prominent as the wavelength decreases. The coupling between the two ports is given by the S12 and S21. The two values should be the same and hence results in a single plot.
Chapter 3. Antenna Concept and Design

The two ports of the antenna are to be fed via a quad-hybrid phase shifter to feed it with a 90° phase difference. The ports then need to be simulated with the phase shift to get accurate data for the S-parameters. The structure is then evaluated with 0° phase in port 1 and 90° phase in port 2. This is important as it gives us the actual reflection co-efficient as seen by the phase shifter. The simulated data for the combined S-parameters are plotted in figure 3.18. Γ is well below the threshold and a bandwidth is established between 2GHz and 13GHz. The antenna is actually matched from 1.5GHz to 14GHz as seen from simulations but we will leave out the frequency monitors outside the purpose of this thesis. The matching only means we have smooth transmission from the feed to the antenna, but an antenna needs to radiate and have the desired pattern and other important antenna parameters.

The main figure of merit for any antenna characterization is the gain. The data for gain obtained from the far-field monitors of the open boundary quad-ridged is
Chapter 3. Antenna Concept and Design

Figure 3.18: Combined Reflection co-efficient

plotted against frequency in figure 3.19. The gain varies from 7.1dB at 12GHz to 10.5dB at 4GHz. It also suggests that the optimum point for this design is at 4GHz where the highest gain is recorded.

Figure 3.19: Maximum gain plotted as a function of frequency,
The figure of merit associated with gain of an antenna is the beamwidth as a cross section of the radiating plane. The data obtained is exported to Matlab and plotted. Beamwidth is a function of the operating frequency. The maximum beamwidth of 60° is seen at 9GHz and a minimum between 4-5GHz. A close look at the gain and beamwidth plots will reveal one is close to a mirror image of the other which is logical since the more directive the antenna, the narrower the beamwidth as power is focused instead of being distributed.

The gain and beamwidth of an antenna means nothing unless it is in the desired direction. The designed antenna is a travelling wave antenna with the desired propagation along $\theta = 0^\circ$ in the XZ-plane. So let’s look at far-field radiation patterns as obtained by the far-field monitors to characterize the antenna performance. Due to constraint of space the data obtained are plotted into four plots each having three frequencies.
Chapter 3. Antenna Concept and Design

Figure 3.21: (a) Radiation Pattern 2GHz, 3GHz, and 4GHz. (b) Radiation Pattern 5GHz, 6GHz and 7GHz.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>max radiation (θ)</th>
<th>Realized gain (dB)</th>
<th>3dB Beamwidth (θ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1°</td>
<td>7.92</td>
<td>71°</td>
</tr>
<tr>
<td>3</td>
<td>1°</td>
<td>9.4</td>
<td>53.5°</td>
</tr>
<tr>
<td>4</td>
<td>1°</td>
<td>10.4</td>
<td>39.2°</td>
</tr>
<tr>
<td>5</td>
<td>2°</td>
<td>10.1</td>
<td>36.3°</td>
</tr>
<tr>
<td>6</td>
<td>5°</td>
<td>8.39</td>
<td>46.3°</td>
</tr>
<tr>
<td>7</td>
<td>14°</td>
<td>8.43</td>
<td>47.4°</td>
</tr>
<tr>
<td>8</td>
<td>16°</td>
<td>8.64</td>
<td>54°</td>
</tr>
<tr>
<td>9</td>
<td>22°</td>
<td>8.16</td>
<td>61.5°</td>
</tr>
<tr>
<td>10</td>
<td>19°</td>
<td>8.54</td>
<td>54.5°</td>
</tr>
<tr>
<td>11</td>
<td>17°</td>
<td>8.47</td>
<td>48.3°</td>
</tr>
<tr>
<td>12</td>
<td>1°</td>
<td>7.09</td>
<td>45.8°</td>
</tr>
<tr>
<td>13</td>
<td>1°</td>
<td>8.44</td>
<td>32.7°</td>
</tr>
</tbody>
</table>

Table 3.3: Antenna characterization with respect to direction of max radiation, Realized gain in the direction of maximum radiation and 3dB Beamwidth.
Chapter 3. Antenna Concept and Design

Figure 3.22: (a) Radiation Pattern 8GHz, 9GHz, and 10GHz. (b) Radiation Pattern 11GHz, 12GHz and 13GHz.

The radiation patterns are plotted in polar coordinates with the realized gain data obtained from CST microwave studio. For realized gain CST optimizes the result by accounting for the all the losses predicted on the basis of the antenna structure and material properties. The radiation patterns are plotted in figures 3.21 and 3.22.

Even though the antenna has an open boundary the radiation patterns seem to emulate that of a conical antenna, directive and exhibiting gain between 7.1dB-10.5dB. The direction of maximum radiation, gain achieved in the same direction, angular 3dB beamwidth $\theta$ is tabulated against the respective frequency which will give a better picture as to what really is happening as far as the radiation is concerned.

Table 3.3 is an illustration of the patterns plotted in figure 3.21 and 3.22. As stated before our desired direction of radiation is $0^\circ$ which is satisfied for most fre-
Chapter 3. Antenna Concept and Design

Figure 3.23: Axial Ratio in dB at boresight $\theta = 0^\circ$ for constant $\phi = 90^\circ$

Figures, A max at 1° is equivalent to a max at 0° since the difference in gain achieved runs in two places of decimal values. The antenna does however deviate quiet a lot between 7-11GHz. A solution to this problem is discussed later. The following figure of merit in this antenna characterization is it’s axial ratio which will dictate the sense of polarization of the antenna.

Figure 3.24: Axial Ratio < 3dB around boresight in degrees.
Chapter 3. Antenna Concept and Design

The axial ratio at boresight of the designed antenna is shown in the discretized plot of figure 3.23. The results are satisfactory from a designer’s point of view since the antenna is circularly polarized at boresight through out the frequency spectrum of interest. But an antenna is not always circularly polarized through out its entire radiating plane. Hence, the need arises to specify the beamwidth where circular polarization is achieved around boresight to better understand the antenna. The characterization is detailed in figure 3.24 and is a function of frequency.


3.6 Ridge-fed Conical Horn Antenna

The open boundary quad-ridge horn antenna is versatile but it does not meet the requirement of a 10dB gain throughout the spectrum as expected and our deployment mechanism is based on the deployment of the conical structure. To improve on these shortcomings of the open boundary, the aperture of the quad-ridge was designed to match the horn aperture and the shape keeping the integration with a conical shroud in mind. The integrated structure is shown in figure 3.25.

![Ridge-fed Conical Horn antenna](image)

Figure 3.25: Ridge-fed Conical Horn antenna.

The Horn aperture was chosen to achieve a minimum gain of 10dB at the lowest frequency and maintain that over the desired frequency range. The feed was adjusted to allow for the added capacitance due to the horn shroud. The feed points are optimized and fed with a discrete port to set up the simulation. A coarse mesh grid is selected to increase computational accuracy. The port impedance is set to 75Ω. The Γ as seen by the phase shifter is plotted in figure 3.26.
Chapter 3. Antenna Concept and Design

Figure 3.26: Reflection Co-efficient Ridge-fed Conical Horn antenna.

Figure 3.27: Gain of the Ridge-fed Conical Horn antenna compared with the gain of the Quad-ridge and plotted against frequency.

The reflection co-efficient shows a good transition at 75Ω. This means we have an antenna impedance matched over the required frequency range. There is a shift at
higher frequencies which is expected due to the capacitance added by the integration of the horn structure and the coupling between the fields of the radiating structures.

After ensuring a smooth transition, the next step is to look for the radiation and how well the antenna is matched to free space. The gain of the antenna is plotted against frequency in figure 3.27 which meets the gain requirement for the design. The gain of the Quad-ridged is also plotted as a comparison.

The gain spiked up, but everything comes at a cost. Here the price is paid in beamwidth of the antenna which is established in the plot in figure 3.28. The increases in gain by an order of magnitude has resulted in a considerable decrease in the beamwidth as predicted. This is a classical trade-off associated with antennas in general, more so in horn antennas [8] [5]. Typically in high frequency transmission systems a directive source is required to compensate for the losses.

Figure 3.28: Angular 3dB beamwidth of the Ridge-fed Conical Horn antenna compared with the Quad-ridged and plotted against frequency.
Chapter 3. Antenna Concept and Design

The next figure of merit for the designed antenna is the axial ratio since circular polarization is critical for operation. The axial ratio at boresight is plotted against frequency in figure 3.29. The entire band is circularly polarized except at 12GHz where it jumps to 3.0416dB which is not exactly desired but optimization can be done to bring that down below the threshold of 3dB. The gain has increased and the beamwidth decreased. The incorporation of the horn has changed the patterns of the Quad-ridged.

The radiation patterns for 2GHz to 7GHz is plotted in dB in figure 3.30(a) and (b). The antenna exhibits nicely formed main lobes for the lower frequencies with 2GHz having the highest beamwidth which gradually decreases and the gain increases. The beam gets directive with frequency and takes the shape of a pencil beam as theorized. At 6GHz, there is substantial destructive interference and needs further optimization.

![Figure 3.29: Axial Ratio in dB at boresight of the Ridge-fed Conical Horn antenna compared with the Quad-ridged and plotted against frequency.](image)
Chapter 3. Antenna Concept and Design

Figure 3.30: (a) Radiation Pattern 2GHz, 3GHz, and 4GHz. (b) Radiation Pattern 5GHz, 6GHz and 7GHz.

Figure 3.31: (a) Radiation Pattern 8GHz, 9GHz, and 10GHz. (b) Radiation Pattern 11GHz, 12GHz and 13GHz.
Chapter 3. Antenna Concept and Design

The patterns for 8GHz, 9GHz and 10GHz are almost identical with a single pencil beam with a high directivity and gain and an angular beamwidth of about 18°. The pattern deteriorates again at 12GHz which is a multiple of 6GHz, which can be purely co-incidental or might be the destructive interference for the wavelength and it’s multiples. The antenna radiates at boresight for the entire band except at 12GHz where the main beam splits in to two, which is common in wideband horn antennas covering over a decade of impedance matched bandwidth [8].

Now, we have a wide band antenna with most of the desired attributes set out to achieve. The antenna can use more optimization and some new techniques can be implemented which would discussed in the conclusion. Next, we move on to the fabrication and measurement of the antennas to prove the functionality of the design.
Chapter 4

Antenna Fabrication & Measurement

The first prototype is fabricated on copper to prove the validity of the design but copper is too heavy and rigid for practical deployment mechanisms. A new material is subsequently investigated to make the design light weight and robust for autonomous deployment and the material is put under test in the succeeding prototype. The fabricated prototypes are measured accordingly and results discussed. The measurement techniques can be referenced in details in [4].

4.1 Prototype X

Prototype X would be the first prototype of a series of prototypes fabricated. It is fabricated on a 2mm copper plate to match the simulations. The design in section 3.6 is fabricated on copper plate using a Computer Numeric Control (CNC) machine. The design for each fin is extracted from CST microwave studio in a 2D .dxf format
which is readable by any autocad software used for mechanical fabrications. The two shapes are cut out from a copper slab and the feed point is marked.

After the fin is fabricated the feed slot is cut on one side of each fin to insert the probe to feed the fin at an optimized location just below the ridges. The feed slot is carefully shaped in a milling machine a fraction of a mm at a time until the desired and simulated feed slot is achieved to fit to insert the probe.

Once the feed slot is perfected the probe is inserted through slot on the arm side to feed the optimized feed point below the ridge on the adjacent arm of the fin. The same procedure is repeated with the other fin and the two fins are soldered and integrated together to form the quad-ridged open boundary horn antenna in section 3.6. For simplicity in the feeding structure the coax is stripped to the dielectric and the outer conductor is grounded on the arm holding the feed. The inner conductor needs to be carefully soldered, keeping in mind the margin for error is 0.2mm since the feed overlaps with each other over such a small gap. A coax probe with a very small
Chapter 4. Antenna Fabrication & Measurement

Figure 4.2: (a) Feed slot milled on the fin side (b) Inserted coax which turns into a probe and feeds the ridge.

inner conductor diameter is recommended and preferred for this application. The fabrication of the feed is of extreme importance and needs high precision instruments to insert the feed and solder it to the optimal point.

4.1.1 Measurement and Results

There are various ways and techniques to characterize and analyze antennas which can be referenced at [1]. We will go through a few of them to characterize our design. The antenna system designed for this thesis ideally needs a 75Ω test bench which was unavailable and hence the antenna was tested on a 50Ω test bench and the results were analyzed and compared to a 50Ω simulation done on the same structure. The first figure of merit would be the S-parameters. The S-parameters are measured using a N5247A PNA-X Network Analyzer.

The measurement is done with a single port calibrated and connected to input
one of a commercial phase shifter from RFLambda which has a frequency bandwidth of 2-18GHz with minimized loss.

Figure 4.3: S-parameter measurement set up for the fabricated quad-ridge.

The measured Γ is plotted against the simulated for 50Ω in figure 4.4.

The measured data shows a clear bandwidth over the entire spectrum even though it is not so in the simulations. That is largely due to the fact that there is a loss associated with the coupler and the cable which is equal to -2.4dB, combined at the highest operating frequency. If that is taken into account the plot will look very close to the simulated one for 50Ω. There is a also an error associated with fabricating the optimized feed at the exact locations and the shape of the structure due to the numerous experiments performed on it. Overall, this result vindicates the design approach taken by the thesis in terms of bandwidth achieved.

The next figure of merit is the gain of the antenna. The antenna gain was measured in the anechoic chamber over a standard sectoral horn antenna from AH systems. The gain was calculated from the power received by the standard horn antenna using a gain transfer method [1]. The gain transfer method is a simple set
Chapter 4. Antenna Fabrication & Measurement

Figure 4.4: Γ comparison between measured and simulated for 50Ω.

up. The power received from the AUT (Antenna under test) is measured first and is replaced by a standard horn antenna and the power level is measured again under the same conditions. The Gain of the AUT then, is given by equation 4.1.

\[
G_{AUT}(dB) = G_S(dB) + 10\log_{10}\left(\frac{P_T}{P_S}\right) \tag{4.1}
\]

Where,

- \(G_{AUT}\) = Gain of antenna under test.
- \(G_S\) = Gain of the standard horn antenna.
- \(P_T\) = Power received from test antenna.
- \(P_S\) = Power received from standard horn.

There is a good amount of loss of power due to the transmission lines, insertion loss of the cables and the phase shifter. The loss is classified according to frequency by manufacturer, that loss is added to the gain to get the absolute gain value. Since the antenna is circularly polarized, the power transmitted in the horizontal and vertical
Chapter 4. Antenna Fabrication & Measurement

plane were measured separately and then the absolute gain of the antenna is given by equation 4.2.

$$G_{AUT}(dB) = 10\log_{10}(G_{TV} + G_{TH})$$  \hspace{1cm} (4.2)$$

Since our antenna is actually operational between 5GHz and 9GHz, gain was measured for only four frequencies and is tabulated below.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Measured Gain (dB)</th>
<th>Simulated Gain (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6.94</td>
<td>10.1</td>
</tr>
<tr>
<td>6</td>
<td>7.89</td>
<td>7.04</td>
</tr>
<tr>
<td>7</td>
<td>7.54</td>
<td>7.53</td>
</tr>
<tr>
<td>8</td>
<td>6.39</td>
<td>6.54</td>
</tr>
</tbody>
</table>

Table 4.1: Measured and Simulated gain results.

The gain values go well with the simulations except for at 5GHz where it is significantly less which is attributed to the fabrication tolerance of the feed structure.

An antenna is chosen by the application based on it’s radiation pattern which is pivotal to operations as stated before. The patterns for all the monitors between 2GHz and 13 GHz for both Vertical and Horizontal axes of the antenna are measured and plotted against the simulated results.

The lower frequencies seem to match better with the simulation than their higher counterpart. As mentioned earlier the fabrication error is high in the prototypes but the radiation patterns for both planes follow the pattern of the simulations if not match exactly.
Chapter 4. Antenna Fabrication & Measurement

Figure 4.5: (a) 2GHz Horizontal radiation pattern. (b) 2GHz Vertical radiation pattern.

Figure 4.6: (a) 3GHz Horizontal radiation pattern. (b) 3GHz Vertical radiation pattern.
Chapter 4. Antenna Fabrication & Measurement

Figure 4.7: (a) 4GHz Horizontal radiation pattern. (b) 4GHz Vertical radiation pattern.

Figure 4.8: (a) 5GHz Horizontal radiation pattern. (b) 5GHz Vertical radiation pattern.
Chapter 4. Antenna Fabrication & Measurement

Figure 4.9: (a) 6GHz Horizontal radiation pattern. (b) 6GHz Vertical radiation pattern.

Figure 4.10: (a) 7GHz Horizontal radiation pattern. (b) 7GHz Vertical radiation pattern.
Figure 4.11: (a) 8GHz Horizontal radiation pattern. (b) 8GHz Vertical radiation pattern.

Figure 4.12: (a) 9GHz Horizontal radiation pattern. (b) 9GHz Vertical radiation pattern.
Chapter 4. Antenna Fabrication & Measurement

Figure 4.13: (a) 10GHz Horizontal radiation pattern. (b) 10GHz Vertical radiation pattern.

Figure 4.14: (a) 11GHz Horizontal radiation pattern. (b) 11GHz Vertical radiation pattern.
Chapter 4. Antenna Fabrication & Measurement

Figure 4.15: (a) 12GHz Horizontal radiation pattern. (b) 12GHz Vertical radiation pattern.

Figure 4.16: (a) 13GHz Horizontal radiation pattern. (b) 13GHz Vertical radiation pattern.
4.2 Material Characterization

Mechanical Engineers at AFRL and Caltech came up with a composite structure made up of highly conductive mesh which would make the antenna light weight and yet act as a perfect conductor which would minimize skin depth for the frequency spectrum and ensure radiation. The composite structure is composed of Phosphor bronze mesh (35µm wire diameter and 325 wires/inch), Astroquartz fabric, Carbon fiber plain weave, epoxy film and conductive epoxy tape. These layers were stacked up in different combinations and tested for conductivity across the surface to characterize the material. The legends for each of these materials are given in figure 4.17.

![Figure 4.17: Legends for the materials](image)

The conductivity of each composite was tested under a four point probe at MTTC, UNM. A four point probe is a simple device which has four probes, two inner and two outer 1mm apart which are a part of an auto mechanical stage which travels up and down to touch the surface of the material to be measured. A high impedance current source is used to supply current through the outer probes and a precision voltmeter measures the voltage across the inner probes. The sheet resistance (Ω/sq)
Chapter 4. Antenna Fabrication & Measurement

$R_s$ is calculated by the equation 4.1 and presented by the probe.

\[ R_s = \frac{\pi V}{\ln 2 I} \]  

(4.3)

The sheet resistance is then converted to bulk resistance by a simple equation given by

\[ \rho = R_s t \]  

(4.4)

where $t =$ thickness of the substrate.

and conductivity($\sigma$) is the inverse of resistance, hence

\[ \sigma = \frac{1}{\rho} \]  

(4.5)

The first two materials were atroquatrz fiber based structures as given by the legends in figure 4.17. The fiber was treated with epoxy film and the mesh on the top. The sample in figure 4.18 (a) is infiltrated and covered with a thin film of non-conductive epoxy while that in (b) is covered with conductive epoxy.

Substrates 3, 4, 5 and 6 are based on carbon fiber with fibers running in orthogonal directions. The variations in the substrates are given by their compositions in layer stack up which is demonstrated in the figures.

Figure 4.18: (a) Substrate 1. (b) Substrate 2.
Chapter 4. Antenna Fabrication & Measurement

Figure 4.19: (a) Substrate 3 (b) Substrate 4.

Figure 4.20: (a) Substrate 5 (b) Substrate 6.

The conductivity calculations are done and given by table 4.2. Substrate 3 was found to be the most conductive among the 6 substrates studied. The overall conductivity of the four substrates which were not coated with the non-conductive epoxy was found to be in the orders of $10^7$ S/m which is comparable to the conductivity of copper at $5.8 \times 10^7$ S/m.

Electrically the high conductivity establishes the viability of these substrates and vindicates the phosphor bronze mesh epoxy composite as a good and light weight alternative for conventional antenna materials which can be deployed from a small satellite platform. The next logical step was to use the material to fabricate a pro-
Chapter 4. Antenna Fabrication & Measurement

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Sheet Resistance (Ω/sq)</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>∞</td>
<td>Non-conductive</td>
</tr>
<tr>
<td>2</td>
<td>0.35mΩ/sq</td>
<td>7.9365 * 10^4</td>
</tr>
<tr>
<td>3</td>
<td>0.285mΩ/sq</td>
<td>9.7465886 * 10^4</td>
</tr>
<tr>
<td>4</td>
<td>∞</td>
<td>Non-conductive</td>
</tr>
<tr>
<td>5</td>
<td>0.65mΩ/sq</td>
<td>4.2735042 * 10^7</td>
</tr>
<tr>
<td>6</td>
<td>0.7mΩ/sq</td>
<td>3.9682539 * 10^7</td>
</tr>
</tbody>
</table>

Table 4.2: Conductivity of the six substrates.

totype and verify radiation efficiency.

In the next section a prototype is fabricated with conductive epoxy and phosphor bronze mesh as the primary radiation element.
4.3 Prototype Z

To validate the functionality of the mesh and epoxy layup and its radiation properties a prototype was fabricated. A High quality EMC foam with a measured dielectric of 1.07 was used as a substrate in this approach.

The first order of business was to shape the fins on the foam (substrate) and the mesh on a milling machine as shown in figure 4.21 a. After the shapes were cut the foam was treated with a layer of conductive epoxy to treat the mesh on the foam surface and also to make it robust to hold the shape of the antenna.

Once the epoxy was layered up on the foam, the mesh was treated on the surface of the foam epoxy layup. The ridge edges were divided into smaller sections and each section was treated separately to make the ridge edge conductive and maintain its curvature. The ridge edges were tightly packed with the help of commercially available binders.

The same procedure was repeated with the other fin and the feed slots were made on the bottom of the arm, right above the slot. The two fins were integrated together
Chapter 4. Antenna Fabrication & Measurement

Figure 4.22: The bounded ridge edge.

to form the Quad-ridged open boundary structure from chapter 3. The feed probe was cold soldered on to the feed point on the ridge edge using conductive epoxy.

Figure 4.23: Prototype Z.
Chapter 4. Antenna Fabrication & Measurement

The resulting structure was stiff, robust and weighs a fraction of its copper counterpart. The structure also exhibited good electrical connections with the feed. The fabricated antenna exhibited a wide band impedance bandwidth but the feed suffered a lot of loss and hence the resulting $\Gamma$ dipped so much below the threshold (which is an anomaly from the simulated result). The fluctuations in the reflection co-efficient was a result of the length of the coax line which was used to feed the antenna. The calibration error can be negated by calibrating at the feed probe end for exact results.

Once proper transmission is established between the feed and the antenna structure this prototype will be characterized further just like Prototype X. Given the electrical properties displayed by this prototype it is expected that this material will work just fine as an antenna material.

![Figure 4.24: Measured reflection co-efficient.](image)
Chapter 5

Contribution and Conclusion

The bottle neck for a high speed downlink between the small satellites and the base station is directly associated with antenna gain and bandwidth. This thesis was based on an engineering approach to enhance the antenna performance on a small satellite platform. The conventional horn design technique was modified to facilitate a deployment mechanism which is pivotal for small satellite integration especially CubeSat platforms. The design meets most of the antenna characteristics set out to achieve which are archetypal to any outer space applications. A new substrate was analyzed and characterized as an alternative for the conventional antenna material to make the design light weight and sturdy for an autonomous deployment once on orbit.

This research is in a nascent state of development. A fully functional prototype fabricated from the proposed substrate is the next step. The radiation efficiencies can be optimized to give a better performance throughout the frequency range of interest. Optimizing a cavity at the shorted side of the truncated conical horn is seen to increase radiation efficiencies. Other techniques should be explored to better antenna performance. It was found that the truncation of the bridges of ridge, and
Chapter 5. Contribution and Conclusion

shorting the arms to the shorting plate resulted in a constant beamwidth across the entire frequency range. Such techniques and more should be investigated, optimized and implemented if proven to increase antenna efficiency.

There is still some distance to traverse between now and the implementation of a likewise wide band horn antenna on a CubeSat. But this can be considered as a start to breaking the stereotype of antennas implemented on a small satellite platform.
References


REFERENCES


