Design and Implementation of Low Mass Short Backfire Antennas using Additive Manufacturing

by

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Abstract

This thesis presents research into the design of low-mass short backfire (SBF) antennas with enhanced performance.

In the first section of this thesis, modern techniques that can be utilized to decrease the mass of the aluminum SBF antenna were introduced. Two different antenna designs were developed using additive manufacturing and perforation techniques. The first design was created by manufacturing the antenna using additive manufacturing techniques, resulting in a significant reduction in mass. Simulations were conducted on this design to analyze the impact of additive manufacturing on the antenna’s performance. The results indicated that the gain was significantly affected by high levels of surface roughness introduced during the manufacturing process. The second low-mass antenna design, the perforated 3D-printed SBF antenna, combines additive manufacturing and perforation techniques. Parametric studies were conducted on this antenna to determine the optimal size, shape, and arrangement of perforations to achieve the best mass reduction and gain results. Simulation studies found that the antenna with a 3x37 circular array of perforations on its rim, each with a radius of 4.5 mm, performed the best. The simulated results were validated by fabricating and measuring the antennas. The mass of the 3D-printed and perforated 3D-printed SBF antennas were approximately 70% and 80% lighter than the aluminum antenna, respectively, while maintaining minimal loss in gain.

The second part of this thesis discusses the enhancement of gain and bandwidth in the SBF antenna. This was done by flaring the rim to increase the aperture size of the antenna. Simulation studies were conducted to examine the impact of rim flaring and rim height on antenna performance. The results of these studies indicate that this technique significantly improved both the gain and bandwidth of the antenna while having minimal effect on the cross-polarization ratio. To further enhance the bandwidth, an iris was introduced to the waveguide feed aperture to obtain better impedance matching. The antenna was then manufactured and tested to confirm the accuracy of the simulations. The measured and simulated results were in excellent agreement.
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Throughout my master’s program, my family and friends have been my primary source of motivation. I am deeply grateful for their unwavering love, encouragement, and support.

Finally, I am deeply grateful to God for giving me this opportunity and for enabling me to see it through.
CONTRIBUTIONS OF AUTHOR


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<th>Description</th>
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<tbody>
<tr>
<td>2PP</td>
<td>2-Photon Polymerization</td>
</tr>
<tr>
<td>2D</td>
<td>2-Dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>3-Dimensional</td>
</tr>
<tr>
<td>ABS</td>
<td>Acrylonitrile Butadiene Styrene</td>
</tr>
<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
</tr>
<tr>
<td>AUT</td>
<td>Antenna Under Test</td>
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<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
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<tr>
<td>CATR</td>
<td>Compact Antenna Test Range</td>
</tr>
<tr>
<td>CSLA</td>
<td>Ceramic Stereolithography</td>
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<tr>
<td>dB</td>
<td>Decibels</td>
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<tr>
<td>DMLS</td>
<td>Direct Metal Laser Sintering</td>
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<tr>
<td>DOD</td>
<td>Drop on Demand</td>
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<tr>
<td>DRA</td>
<td>Dielectric Resonator Antenna</td>
</tr>
<tr>
<td>EBG</td>
<td>Electromagnetic Band-gap</td>
</tr>
<tr>
<td>ECal</td>
<td>Electronic Calibration</td>
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<tr>
<td>EM</td>
<td>Electromagnetic</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>ERA</td>
<td>Electromagnetic Band-gap Resonator Antenna</td>
</tr>
<tr>
<td>FDM</td>
<td>Fused Deposition Modelling</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
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<td>FPC</td>
<td>Fabry-Perot Cavity</td>
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<td>FSS</td>
<td>Frequency Selective Surface</td>
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<td>GHz</td>
<td>Gigahertz</td>
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<tr>
<td>HFSS</td>
<td>High-Frequency Structure Simulator</td>
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<td>HIPS</td>
<td>High Impact Polystyrene</td>
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<tr>
<td>HPBW</td>
<td>Half Power Beamwidth</td>
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<td>JMT</td>
<td>Jet Metal</td>
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<td>LL</td>
<td>Luneburg Lens</td>
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<td>MHz</td>
<td>Megahertz</td>
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<td>Mm</td>
<td>Millimeter</td>
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<td>Abbreviation</td>
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<tr>
<td>PLA</td>
<td>Polylactic Acid</td>
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<td>PR</td>
<td>Perforation Radius</td>
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<td>PRS</td>
<td>Partially Reflective Surface</td>
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<td>PVA</td>
<td>Polyvinyl Alcohol</td>
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<td>RCA</td>
<td>Resonant Cavity Antenna</td>
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<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
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<td>SBF</td>
<td>Short Backfire</td>
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<tr>
<td>SLA</td>
<td>Stereolithography</td>
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<td>SLL</td>
<td>Side Lobe Level</td>
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<td>SLM</td>
<td>Selective Laser Melting</td>
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<td>SR</td>
<td>Surface Roughness</td>
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<tr>
<td>STL</td>
<td>Standard Tessellation Language</td>
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<tr>
<td>THz</td>
<td>Terahertz</td>
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<tr>
<td>UV</td>
<td>Ultra-violet</td>
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<tr>
<td>VNA</td>
<td>Vector Network Analyzer</td>
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<tr>
<td>VSWR</td>
<td>Voltage Standing Wave Ratio</td>
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1. Introduction

This thesis presents research in the design of short backfire antennas that are constructed using additive manufacturing techniques. The main objective was to reduce the mass of the antennas versus conventional metallic structures while maintaining similar performance. This process involved the use of lightweight materials instead of traditional solid metals. The perforation technique was also used in addition to the additive manufacturing technique to achieve a more significant reduction in mass. Once this was achieved, further investigations into gain, impedance bandwidth, and cross-polarization bandwidth were successfully performed. The antenna flaring technique was employed to enhance the gain and bandwidth of the SBF antenna in a new design. Many studies were conducted to achieve the optimal designs presented in this thesis. The designs were verified by building prototypes and successfully testing them in the Electrical and Computer Engineering (ECE) department’s Antenna Lab. The motivation for this thesis work is presented in the following section.

1.1 Motivation

As each new satellite mission is launched, customers’ demand for more capabilities increases. This is resulting in the need for larger satellite payloads. Some of these current satellite missions include “Canada’s RADARSAT Constellation Mission (operates in C-band like the short backfire antennas presented in this work) [1]” “Deep Space Climate Observatory [2]”, “Global Ecosystem Dynamics Investigation Lidar [3]”, and “Ice, Cloud, and land Elevation Satellite [4]”. Because of their increased functionalities, manufacturers must expand the size, weight, and power of their satellite command and telemetry systems and the payload [5]. This also applies to drones for search and rescue missions, cargo delivery, and remote sensing. Engineers often have to choose between having a longer flight time or increasing the weight of the payload. While improving the functionality is necessary in most cases, this can adversely affect the launch cost of satellites and reduce the flight time of drones. This is because a larger platform weight has a higher energy demand to reach orbit or to maintain flight.

Reducing the aircraft’s overall weight by constructing lighter components is one of the best ways to address this problem. However, it might not be easy to do so without sacrificing functionality.
For example, when using a drone for mapping purposes, one can either opt for a standard RGB camera that requires about 5 to 6 lithium batteries for power or switch to a higher resolution camera that captures improved quality images. However, the latter option uses twice the amount of batteries and significantly increases the weight of the payload, resulting in a trade-off between image quality and flight time [6]–[8]. For these reasons, it is essential to look into ways to reduce the size and weight of the payload while maintaining the same functionality. The antenna is one of the vital components of these systems, and its mass can vary depending on the type, construction, and capabilities. This can pose a major problem, especially for drones, as the antenna weight can be a considerable portion of the payload. System performance can be enhanced, and overall operating expenses can be reduced by reducing the weight of the antenna.

Various techniques have been employed in literature to reduce the antenna weight. These techniques include additive manufacturing using lightweight materials, applying perforation techniques, and replacing solid metals with conductive textile materials, to name a few. In recent years, a variety of additive manufacturing techniques, such as photonic polymerization, stereo lithography, polyjet printing, and fused deposition modeling (FDM), have been utilized to manufacture antennas and electromagnetic components [9], [10]. Every method has advantages and disadvantages that are suitable for creating different types of antennas. These techniques will be explained in detail in the next chapter. The perforation technique has been implemented in the literature by either drilling holes or making slots in the material that resemble a mesh or grid and contain numerous tiny holes [11]–[13]. Due to the removal of antenna sections and redistribution of surface current, it is almost inevitable that certain losses will occur despite the technology successfully reducing antenna weight. To minimize these losses, selecting the appropriate hole/slot size and the distance between them is crucial [14].

Aside from the weight, the performance of these antennas plays a vital role in the quality of signals transmitted and received and, in turn, the efficiency of the system. The data collected by a remote sensor or a satellite is only as good as the signal it transmits back, and the quality of the signal depends on the antenna used to send it [15]. Modern satellites and drones are equipped with various antennas designed to broadcast and receive electromagnetic radiation pulses, enabling the transmission and reception of data. As these antennas are required to have high gain, directivity, low volume, lightweight, and low cost, the short backfire (SBF) antenna is an excellent choice to
meet these specifications [16]–[18]. Although many SBF antennas have been designed that meet many of these parameters, further research is needed to improve performance and efficiency. It is particularly demanding to meet multiple specifications simultaneously while reducing the overall antenna mass, and this thesis addresses this challenge.

It is possible to enhance the performance of the SBF antenna by utilizing various gain-enhancing methods implemented in numerous other types of antennas, including horn and waveguide antennas. These techniques have also been covered in the background chapter. One technique involves using multiple antennas as an array to enhance the antenna’s overall gain and directivity by combining the gain of each element [19]–[21]. However, implementing this approach can be costly and complex as some designs require a complicated feed network and multilayer architecture [22]. Another method to improve the performance of the SBF antenna is to increase the aperture phase to maximize its efficiency. This can be achieved by using metasurfaces, such as electromagnetic bandgap (EBG) materials, partially reflecting surfaces (PRS), or meta-surface lenses placed over the opening of the antenna aperture [23]–[25]. This method has been studied in the literature and has shown promising results. Metamaterials have been used to increase horn antenna gain, but their narrow bandwidth and complex design are limitations [26], [27]. Increasing the physical aperture size of an antenna is another popular method for gain enhancement [28]–[30]. The horn antenna, which is essentially a flared waveguide antenna, is an example of how the size of the aperture can be expanded by flaring the opening of the antenna. This technique addresses the problem of low impedance matching at the edge of the antenna by minimizing the reflected signal and maximizing the antenna’s efficiency [31].

1.2 Thesis Outline

This thesis is structured into five chapters. Here is a brief overview of the contents of each chapter.

Chapter 1 of this thesis provides an introduction that outlines the motivation, objectives, and thesis structure.

Chapter 2 of this thesis offers background information on the topics that will be presented in the subsequent chapters. This chapter consists of four sections, which provide insight into the
following: 1) Additive manufacturing, 2) Techniques for enhancing antenna gain, and 3) Antenna design theory, antenna parameters, measurement techniques, and 4) The short backfire antenna.

Chapter 3 presents a study on mass reduction techniques applied to a C-band short backfire antenna. Two designs of the antenna are discussed: a 3D-printed short backfire antenna and a perforated 3D-printed SBF antenna. The first design achieves mass reduction through additive manufacturing, while the second combines perforation and additive manufacturing techniques to achieve even greater mass reduction. The fabrication process, measurement procedures, and results used for design verification are explained in detail.

Chapter 4 discusses how the C-band SBF antenna design can achieve gain and bandwidth enhancement by using the aperture flaring technique. Parametric studies are presented to examine the effects of the flaring angle on the antenna’s performance. The antenna design was verified by fabricating and measuring it.

This thesis concludes with Chapter 5, which presents a summary of the findings from the studies conducted in this thesis and recommendations for further development.
2. Background

2.1 Introduction

This chapter includes pertinent background information on the four main subjects that serve as the foundation for this thesis: 1) Mass reduction of the short backfire antenna and 2) Gain and bandwidth enhancement of the short backfire antenna. The second section of this chapter describes important antenna parameters useful for the designs in this thesis. Methods for enhancing the gain and bandwidth of antennas are discussed in the third section. In the following section, the design of the short backfire antenna is explained including the effects of the individual antenna parts on the overall performance. The final section of this chapter provides information on common additive manufacturing techniques, different types of 3D printed antennas based on their materials, as well as the advantages and challenges of additive manufacturing.

2.2 Antenna Theory and Design Principles

2.2.1 Antenna Parameters

This sub-section presents the important parameters of antennas that will be used to describe their performance. These include radiation pattern, input impedance, bandwidth, gain, and polarization. As these parameters will be frequently mentioned in this thesis, a brief explanation of each one is important to understand their significance.

Radiation Pattern: The definition of an antenna’s radiation pattern, also known as the antenna pattern, is “a mathematical function or a graphical representation of the antenna’s radiation properties as a function of space coordinates”[32]. The properties of radiation include directivity, phase or polarization, radiation intensity, radiation flux density, and field strength. The linear plot of a radiation pattern is shown in Figure 2.1. The radiation pattern consists of several lobes which are categorized into major and minor lobes. The major lobe shows the direction of where the radiation is maximum, all other lobes are referred to as minor lobes and this includes side and back lobes. Minor lobes are usually unwanted as they decrease the antenna efficiency, and therefore it is necessary to keep them as low as possible.
Typically, the area around an antenna is split into three sections: a) reactive near-field, b) radiating near-field, and c) far-field regions.

A. Reactive near-field: The area of the near-field region directly surrounding the antenna where the reactive field is predominant is known as the reactive near-field region. The radius of this region from the antenna \( R_1 \) is given below where \( D \) and \( \lambda \) are the largest length and wavelength of the antenna respectively:

\[
R_1 < 0.62 \sqrt{\frac{D^3}{\lambda}} \quad [32].
\]

B. Radiating near-field: This is the radiating region between the reactive near field and the far-field region where the angular field distribution is dependent on the distance from the antenna. The range of the distance of this region from the antenna is given as \( R_2 \):

\[
0.62 \sqrt{\frac{D^3}{\lambda}} < R_2 < \frac{2D^2}{\lambda} \quad [32].
\]

C. Far-field region: The far field region is the radiating region around the antenna where the angular field distribution is not dependent on the distance from the antenna. Antenna gain and polarization measurement requires a plane wave illumination for accurate measurement, this only occurs in the far-field region. The far field region \( R_3 \) can be expressed as:

\[
R_3 > \frac{2D^2}{\lambda} \quad [32].
\]

**Input Impedance:** “The impedance presented by an antenna at its terminals or the ratio of the voltage to current at a pair of terminals or the ratio of the appropriate components of the electric to magnetic fields at a point” describes the input impedance of an antenna [32]. The antenna’s input impedance consists of resistive and reactive impedances. The antenna is usually connected
to a signal generator that also has its own reactive and resistive impedance. To achieve the highest power transfer from a generator to the antenna, it’s necessary to ensure that the reactive and resistive impedances of the antenna match the reactive and resistive impedances of the generator, respectively. If there’s a mismatch, signal loss due to reflection will occur, which can negatively impact the efficiency and frequency bandwidth of the antenna. The amount of reflected signal can be measured using the vector network analyzer (VNA). The equation of the reflection coefficient ($\Gamma$) of an antenna also known as S11 is provided below [33].

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

where $Z_L$ is the impedance seen at the input of the antenna while $Z_0$ is the characteristic impedance of the VNA which is usually 50Ω in most cases [33]. For many antennas including SBF antennas, a reflection coefficient equal to or lower than -10 dB (representing a 90% signal power transmission) is acceptable for good performance.

**Bandwidth:** “The range of frequencies within which the performance of the antenna, with respect to some characteristic, conforms to a specified standard” is the definition of an antenna’s bandwidth [32], [34]. The range of frequencies on either side of a center frequency where the antenna characteristics such as radiation efficiency, side lobe level, gain, beam direction, input impedance, pattern, beamwidth, polarization, and side lobe level fall within an acceptable range of those at the center frequency are referred to as the bandwidth. For instance, the impedance bandwidth of an antenna is the range of frequencies where the S11 result is below -10 dB.

**Gain:** When compared to the theoretical isotropic radiator, an antenna’s gain indicates its capacity to emit a signal in any direction. Usually, antenna gain is expressed in decibels in relation to isotropy (dBi) [34]. The expression of gain takes the antenna’s efficiency as well as its directivity into account. Different applications require different gain levels, for example, satellite communication which is a long-distance communication usually requires high gain and directive antennas while in wireless network applications, broader radiation area which results in lower gain is prioritized [35]. Short backfire antennas can achieve high gain of about 15-20 dBi [36], which makes them suitable for applications such as remote sensing that require a minimum gain of about 14 dBi.
**Polarization**: The polarization of a wave can be simply defined as the direction of the vector describing its electric field. There are three types of polarization: elliptical, circular, and linear. If the direction of electric field vector is in a straight line, then the field is linearly polarized but if it is circular or elliptical then the field is referred to as circularly or elliptically polarized respectively [32], [34].

The polarization of a wave is often resolved into the co-polarization and cross-polarization, two orthogonal polarizations, at each point on the radiation sphere. The polarization that the antenna is designed to transmit or receive is known as co-polarization, and the polarization that is orthogonal to the co-polarization is known as cross-polarization [32]. Cross-polarization should have a value of zero in an ideal condition where the antenna is purely polarized. Purely polarized antennas do not exist in real-life therefore, there is usually some amount of unwanted cross-polarization, therefore, many antenna designs aim to decrease this value to as low as possible [37].

### 2.3 Gain and Bandwidth Enhancement Techniques

#### 2.3.1 Partially Reflecting Surface

Many antenna researchers have been drawn to the idea of using a “partially reflecting sheet array” superstructure to significantly increase gain and directivity since Trentini first presented it in 1956 [38]. The reasons for this widespread interest include the concept’s elegant theoretical design, its connections to other well-researched areas like leaky waves, electromagnetic bandgap (EBG) structures [23], frequency selective surfaces, and metasurfaces [26], as well as its practical benefits as an easy, low-cost means of achieving high gain from an efficient planar antenna without the need for an array, which usually requires a feed network. Antennas designed using this concept go by several names currently, including two-dimensional leaky-wave antennas, partial reflector surface (PRS) based antennas, Fabry-Perot resonant cavity (FPC) antennas, Resonant Cavity antennas (RCA), and (EBG) resonator antennas (ERAs) [39].

The primary radiating element inside the cavity can be an open-ended waveguide, patch antenna, stacking antenna, dielectric resonant antenna (DRA), dipole antenna, or crossed bowtie dipole. Depending on the antenna type, there may be variations in the PRS layer configurations. Either a periodic structure made up of a series of metallic unit cells or a whole dielectric structure can be
used. The reflective surface of the PRS structure causes multiple reflections within the formed cavity. By superimposing in-phase transmitted waves and using the proper cavity thickness (which is the distance between the PRS and the ground plane), the antenna gain can be greatly increased. The antenna’s performance in terms of gain, bandwidth, beam angle, and aperture efficiency is significantly impacted by the phase and magnitude of the PRS reflection behavior [40].

An example of an FPC antenna is shown in Figure 2.2, where a probe-fed patch antenna is the primary radiating element and the PRS is a 9x9 array of circular holes in a metallic sheet. The FPC mode is excited at the desired frequency when the S11 presents a 180° reflection phase as seen in Figure 2.3.

Figure 2.2. Geometry of an FPC antenna (a) front view; (b) top view of the frequency selective surface (FSS); (c) top view of the feeding patch [40].
The radiation performance is reduced by the non-uniform aperture phase and magnitude distribution of conventional cavity antenna configurations. One efficient way to improve antenna directivity and lower side lobe level is to compensate for the irregular field distribution of the aperture [42]. While some studies have examined aperture magnitude compensation to improve antenna performance, others have concentrated on phase compensation. A few investigations have shown that compensating for both phase and magnitude results in an impressive aperture efficiency [43]. The most popular technique for compensating for the non-uniform phase and magnitude distribution of the electric field over the antenna aperture is to use a non-uniform PRS structure as shown in Figure 2.4.

Figure 2.3. Reflection characteristics of the cavity under normal incidence using a unit cell model [41].

Figure 2.4. Configuration of an RCA with an aperture phase distribution compensation: (a) Schematic; (b) Fabricated prototype [44].
Although the PRS technique has been effective in increasing antenna gain, it has some drawbacks that would make it challenging to use for the SBF antennas in this thesis. These drawbacks include the complex design of the PRS and the narrow bandwidth. The resonant structure of the cavity antenna limits the bandwidth of the antenna as it determines the band of operation, which is usually very narrow [45], [46]. Furthermore, making modifications to improve the bandwidth and compensate for the irregular field distribution further increases the size and complexity of the design as seen in Figure 2.4 where the PRS is much larger than the antenna. This presents a challenge for the antennas in this work, as reducing mass is a key objective of the thesis.

2.3.2 Antenna Arraying Technique

Creating an assembly of radiating elements in an electrical and geometrical structure, which is known as an array, is another technique to increase the antenna’s dimensions without necessarily increasing the size of the individual elements. The unit components of an antenna array are usually identical although not in all cases [32]. The vector sum of the fields generated by each element determines the array’s total field. In other words, coupling is neglected, and it is assumed that each element's current is equal to that of the isolated element. The fields from the array’s elements must interact constructively (add) in the intended directions and destructively (cancel each other) in the remaining space to produce highly directional patterns. This method is popularly used for microstrip patch antennas and reflector antennas where multiple elements are arranged in a way that the directivity and gain are maximized. The gain of a single patch antenna can range from 6-9 dBi, whereas the series-fed 8x4 patch array presented in [47] with 32 elements produced a high gain of 18 dB at 60 GHz as a result of the multiple elements.
While the arraying technique is a very efficient and relatively straightforward approach to increase gain, certain designs need a very complicated feed network and multi-layer architecture [22], which drives up the cost and complexity of the antenna. Due to the fact that using several antennas increases the final antenna size, this approach may be difficult for applications with limited antenna space and for antennas that are not as compact as printed antennas.

2.3.3 Aperture Flaring

Another well-known method of gain improvement that can be applied to SBF antennas is the technique of increasing the physical aperture size of the antenna [29], [30], [48]. An example of this technique can be seen in the horn antenna which is a waveguide antenna with a flared opening [49]. Flaring the waveguide antenna’s aperture increases the efficiency of signal transmission and in turn, increases the antenna gain. The lower efficiency is because the impedance of signals changes abruptly from the waveguide to free space, which is around $377\,\Omega$. This abrupt change in impedance causes signals to be reflected as standing waves along the waveguide, which is comparable to having poor matching at the end of transmission lines made of wire, such as coaxial [31]. The wider aperture feature in the horn antenna helps to convert the abrupt discontinuity of the wave into a progressive transition enabling the forward radiation of most of the input signal hence improving the radiation efficiency and directivity of the beam.

Figure 2.5. An 8x4 series-fed patch antenna array for 60 GHz [47].
The directivity and gain of the antenna are significantly impacted by the flaring angle. The gain rises with increasing flaring angle and aperture size. There is an ideal angle, though, at which the gain starts to decline as the flare angle increases. This is because the gain is canceled out by the growing phase error which is the phase difference between the edges and the center point [20]. Because the flaring angle necessary to obtain better gain is small, the increase in antenna area is not significant, and the bandwidth is unaffected. An example of how the flaring technique was used to enhance other antenna designs is presented in [29]. The gain of a cavity-backed antenna in this work was enhanced from 10.2 dBi to 12.8 dBi by flaring the cavity wall’s upper section as shown in Figure 2.6.

![Diagram of flared octagonal cavity-backed radiating open prism antenna](image)

Figure 2.6 Geometry of the flared octagonal cavity-backed radiating open prism antenna [29].

### 2.4 Short Backfire Antennas

The short backfire (SBF) antenna is a type of leaky cavity resonator invented by Herman W. Ehrenspeck in 1965 [50]. In recent years, the SBF antenna has gained popularity because of its compactness, high performance, simple and low-cost fabrication process, and its high isolation from surrounding EM radiation. As a result of these attractive characteristics in addition to its ruggedness, the SBF antenna has been used as feed antennas for reflector antennas, telemetry, mobile satellite communications, and remote sensing in extreme conditions.

The geometry of the dipole fed SBF antenna proposed by Ehrenspeck is shown in Figure 2.7. The geometry of Ehrenspeck’s short backfire antenna [52]. [50]–[52]. The antenna consists of two
reflectors, \( R_1 \) and \( R_2 \), a rim (H) and a dipole antenna feed (F). The leaky wave cavity is formed between the two reflectors with different diameters. The top smaller reflector also known as the sub-reflector, \( R_1 \) is separated by about half a wavelength from the larger reflector (main reflector), \( R_2 \). The sub-reflector serves as a diffracting obstacle for the feed radiation and creates the “leaky” cavity wall, while the main reflector absorbs most of the energy emitted by the feed, which is positioned near the middle of the cavity. To reduce side and back radiation of the cavity, a metallic rim, H is designed to surround the main reflector which increases the antenna gain by 1 dB [53].

![Figure 2.7. The geometry of Ehrenspeck’s short backfire antenna [52].](image)

A. **Antenna length**: The length of the antenna \( L_A \) is basically the distance between the main reflector and the sub-reflector. The short backfire antenna is a special form of the backfire antenna; therefore, it is expected to satisfy the following condition:

\[
L_A = n \frac{\lambda_S}{2} + \Delta L, \quad \text{for } n = 1, 2, 3, \ldots
\]

where \( \lambda_S \) is the wavelength, \( \Delta L \) is the length correction due to the radiation, and \( n \) is a real integer, called the standing-wave number. However, experimental studies have shown that the length, \( L_A \) of the long backfire antenna takes discrete resonance values, equal to \( n \) free-space half wavelength, therefore reducing the expression to:
\[ L_A = n \frac{\lambda_S}{2} \]

In the case of the short backfire antenna, \( n = 1 \), therefore \( L_A \) is simply \( 0.5\lambda_S \). This value can be increased to as high as \( 0.75\lambda_S \) to increase the gain and bandwidth [51].

B. **Main Reflector**: The diameter of the main reflector is proportional to the quantity of reflected energy and the phase difference between the aperture-field distributions caused by the edge radiator (rim) and feed (F) in the aperture plane. For a short backfire antenna with a length \( L_A = 0.5\lambda_S \), the main reflector diameter, \( D_2 \) typically has a value of about \( 2\lambda \). Reducing the diameter will cause a reduction in the realized gain [51] because of the reduction in aperture size. Increasing the dimension of the diameter does not necessarily increase the gain unless it is accompanied by an increased length and rim height, \( w \) [53].

C. **Sub-reflector**: The amplitude and phase field distribution in the antenna’s aperture are mostly influenced by the sub-reflector’s dimension. If the sub-reflector is too small, the antenna becomes a regular antenna with just a radiating feed and a reflector cavity which reduces the antenna’s gain. Similarly, the gain is also reduced when the dimension of the sub-reflector is too large, as this reduces the size of the aperture. Although the sub-reflector’s diameter can range between \( 0.3 \lambda \) - \( 0.7 \lambda \), for optimum performance \( D_1 = 0.5 \lambda \) [51].

D. **Rim Width**: The antenna’s gain is increased when a rim is added to the main reflector, by lowering the levels of the side lobe and back lobe. Although the rim width’s normal value is typically \( w = 0.25 \lambda \), it can range from \( 0.25 \lambda \) to \( 0.7 \lambda \). For short backfire antennas with high gain values (between 15 - 20 dBi) which is applicable to the SBF antennas presented in this thesis, rim width values up to \( 0.57 \lambda \) to \( 0.7 \lambda \) are required.

The performance of the SBF antenna in terms of the gain, impedance bandwidth, and cross-polarization ratio is also dependent on the type of feed antenna employed. The three major types of feed antennas used to excite the SBF antenna include the dipole antenna, the microstrip patch antenna, and the waveguide antenna. Each excitation technique has its advantages and drawbacks, and the decision on which to choose is based on the application of the SBF antenna.
The half-wave dipole antenna is the most widely used excitation for the SBF antenna because of its simple design. An example of this type of feed design can be seen in the dipole excited hard walled SBF antenna shown in Figure 2.8 [54], where vertical metal strips are placed on the inside wall of a conventional SBF antenna and separated at a distance (ert) from the rim by a low index dielectric material as a way to obtain higher efficiency and gain. Unfortunately, because the dipole-excited SBF is essentially a leaky cavity structure, the input impedance bandwidth (<-10 dB) is very narrow. For a cross-dipole feed, while they are able to provide a high gain of 13-15 dBi, the inherent impedance bandwidth without a matching circuit is only 3–5% for a voltage standing wave ratio (VSWR) less than 1.5 [55]. For a single-dipole excited SBF, the bandwidth is considerably worse at around 1% [56].

![Figure 2.8. Geometry of hard-walled SBFA [54].](image)

Exciting the SBF antenna with microstrip patch antenna has the advantage of a compact structure, low mass and low cost of fabrication compared to the dipole and waveguide fed types. The gain for the patch antenna fed SBF antenna is also in the range of 13-15 dBi. While the simple rectangular patch antenna provides a narrow impedance bandwidth (3-5%), more complex designs like the design illustrated in Figure 2.9 have been developed to increase the bandwidth to as high as 11-15% [57]. Two H-shaped slots that were electromagnetically coupled to a broadband hybrid coupler were used to feed the patch element. This allowed for dual circular polarization and a wide bandwidth to be retained. However, the cross-polarization ratio was affected.
Compared to the other feed types, the waveguide antenna feed has the advantage of having a high-power capacity, compact design, and ease of integration with other excitation components, for example, the waveguide-fed SBF antenna shown in Figure 2.10 has been integrated with the orthomode transducer to achieve dual polarization [36]. Another advantage is that the impedance bandwidth can be easily increased to about 30% or more [58], which is not possible with the other feed types.
2.5 Additive Manufacturing

In additive manufacturing (AM), machinery is controlled by computer-aided design (CAD) software or 3D object scanners to deposit material in precise geometric shapes layer by layer. AM creates objects by adding material, as the name suggests. On the other hand, the traditional methods of creating an object frequently require the removal of material by milling, machining, carving, sculpting, or other methods. While the phrases “rapid prototyping” and “3D printing” are sometimes used interchangeably when discussing additive manufacturing, each technique is essentially a subset of additive manufacturing [59]. The popularity of additive manufacturing technology has increased in recent years due to its capability to produce lightweight objects, reduced cost of production, and its ability to produce complex designs using simple methods when compared to other manufacturing processes [60], [61].

The additive manufacturing process of obtaining a solid object from a CAD model is given in Figure 2.11. The first step involves creating the model of the desired object using CAD software such as SolidWorks [62], and AutoCAD [63], [64]. The model is then transformed from the CAD file into an STL (standard tessellation language) file, which is a common file format for additive manufacturing. The industry standard for data transfer between CAD software and a 3D printer is the STL file format. The data for every surface of the 3D model is stored in the STL file which is composed of triangulated sections with defined vertex coordinates. The resolution of the printed object can be improved by increasing the number of triangles per surface [65],[64]. The 3D printer uses its built-in slicer software to transform the STL file into a G-file, which is then used to interpret the digitally provided coordinates from the file. G-files split 3D STL files into a series of 2D horizontal cross sections (25–100 μm, determined by the fabrication method). This enables the 3D object to be printed in successive layers of the desired material, beginning at the base and building the model from a set of 2D layers obtained from the original CAD file [66], [67].

Post-treatment care is typically necessary for 3D-printed objects. The extent and method of treatment are determined by the AM process employed, the replication procedure, the desired application, and the required level of quality for the prototype. The process of post-processing involves removing the 3D-printed part from the machine along with the 3D-printed support structures used for supporting the object during the printing process. For AM techniques involving
liquid materials, support structures are usually needed to prevent levitating layers and stabilize the part while it is being built, and to avoid deformations and overhanging portions. To assure the part’s endurance, post-treatment can also involve surface finishing techniques like sandblasting, sealing, or coating. For applications that require the printed object to have a conductive surface, polishing the surface is very important to minimize surface roughness[64].

![Additive manufacturing process](image)

Figure 2.11. Additive manufacturing process.

### 2.5.1 Additive Manufacturing Techniques

There are several categories of additive manufacturing techniques, and they can broadly be classified into the following:

A. Photopolymerization
B. Lamination
C. Powder-based
D. Extrusion

Each of these techniques has its specific application, therefore there are no arguments over which one is superior. These days, 3D printing technologies are rapidly being used to produce a wide range of parts that are sold commercially rather than just prototypes.

**A. Photopolymerization**

Photopolymerization, which generally refers to curing photo-reactive polymers, or photopolymers, with a laser, UV light, or other light source was one of the first AM process to be employed and the most commonly used technique in membrane manufacturing [68]. Hideo Kodama developed a technique in 1981 that utilizes UV radiation to cure a photo-hardening polymer, enabling the creation of three-dimensional objects. When the liquid polymer is exposed to UV radiation, it solidifies at the surface. Subsequent layers can solidify and be built one on top of the other with good adherence until a final 3D shape is made [69]. Some of the 3D printing techniques that
employ the photopolymerization process include stereolithography, polyjet, and two-photon polymerization.

Stereolithography (SLA) is the most widely used laser-lithography-based method [68]. The cross-section of the model is traced and cured using an ultraviolet (UV) laser, leaving the remaining portion liquid. The platform is lowered, and a fresh layer of resin is applied to the part after the trace is finished. To obtain the complete piece, this process is repeated. The final component is subsequently placed in an ultraviolet oven to finish the curing process[68]. SLA is capable of operating in the mmWave bands and producing high-resolution parts with smooth surfaces due to its small feature size of about 50 μm[64]. SLA can be further classified as ceramic SLA (CSLA) and polymer SLA depending on the type of material used. High-filtering and RF packaging applications have achieved success using Polymer SLA. Nevertheless, polymers and polymer SLA are inappropriate for low-loss mmWave applications because they are lossy at microwave frequencies. Ceramic-only pieces can be created by employing post-sintering and de-binding techniques after printing to remove the polymer percentage and leaving only the ceramic parts [70].

Polyjet technology, which is based on the same principle as photopolymerization, uses inkjet technologies to deposit photocurable materials at precise locations determined by the layer design. The idea behind inkjet 3D printing is similar to that of conventional paper printers. Light-curable resins are used by the 3D printers in place of standard inks. Two distinct resists are used by inkjet 3D printers; the support material, which is eliminated after the build process, and the main construction material, a UV resist [64], [69]. The layer is then quickly hardened by full area UV light irradiation that follows. Support material is also deposited for intricate designs to help the printed structure stand alone. Inkjet printing is classified into two types: continuous and drop-on-demand (DOD). Continuous inkjet printing uses electrostatic plates in the printer head to drive ink droplets onto paper for printing or into a trash compartment for recycling and reuse. By applying a pressure wave pattern, the droplet size and spacing may be adjusted. The DOD technique uses a voltage and pressure pulse to control the ink droplet, removing the requirement for waste ink separation from the printer head [65].

Another photopolymerization technique is the two-photon polymerization (2PP). The basis of the 2PP, which is a direct laser writing technique, is the crosslinking of photopolymers caused by ultra-
short femtosecond laser pulses at a wavelength of 800 nm. Two laser beams are focused into a bath of liquid resin, where a tightly localized photopolymerization is induced within a heated zone. When a photo initiator simultaneously absorbs two near-infrared photons, the photochemical reaction begins, which causes the resin to cure rapidly. One way to direct the laser focus is to move the item three-dimensionally using a positioning system such as piezoelectric stages or to scan the x/y-plane with a scanner while the object is moving in the z-direction. Because of its high numerical aperture immersion oil objective, an x/y galvo scanner concentrates the laser pulses to form microstructures [71], [72].

B. Lamination

The lamination technique is used to create 3D parts by stacking layers of specific sheet materials, such as metal, paper, and plastic. A laser or razor is used to outline the intended cross-section once the first layer of sheet material has been put onto a stage to define the pattern on the layer. A second layer covers the first layer once the extra material from the sheet is removed, and the next pattern is defined by laser or knife tracing, which is based on the data from the STL file. Adjacent layers are joined together using adhesives or welding, depending on whether the material is paper or metal. A layered 3D model can be produced by repeating these procedures [73], [74].

C. Powder-based

This additive manufacturing technique uses solid materials (particulates ranging from 50 to 100 μm) as building blocks for the 3D object [69]. The idea behind the printing process is similar to that of photopolymerization, except that powder is used instead of liquid photopolymer and it is applied in thin layers to the building stage using rollers or squeegees. The particles are now joined together at precise locations according to the cross-sectional model design by a binding system (mostly liquid glue or laser beams) directed onto the powder layer. The stage is lowered to distribute a second layer of powder on top of the first once the solid layer has formed, readying the mixture for the subsequent binding step [64], [69], [70].

Selective laser sintering is a type of powder-based AM technique where a high-power laser is used to sinter powder photopolymers to form a 3D object. The laser beam is selectively scanned over the powder to raise the local temperature to the melting point of the powder to fuse the powder particles together, according to the cross-sectional profiles specified in the STL file. A second layer
of powder is applied, levelled, and sintered in the appropriate places once the first layer is finished [64], [68], [69].

D. Extrusion

Extrusion-based 3D printing technologies typically include deposition of the model material (and/or support material) straight from a nozzle head dispenser following material pretreatment such as liquefaction. Fused deposition modeling (FDM), developed by Stratasys’ Scott Crump, is one of the most frequently utilized extrusion-based AM technologies today. The process of FDM shown in Figure 2.12 involves the layer-by-layer deposition of semi-molten thermoplastic materials by a machine with a movable head onto a stage through extrusion, providing a 3D model. For the construction material to solidify quickly (around 0.1 seconds) after extrusion and cold-weld to the preceding layers, it is heated to 0.5°C above its melting point. Considerations for this technique include the need for a consistent nozzle speed and material extrusion rate, the installation of a support structure for components that overhang, and the head’s speed, which has an impact on the thickness of the entire layer [65], [67].

![FDM - ADDITIVE MANUFACTURING](image)

Figure 2.12 Fused deposition modelling additive manufacturing technique [77].

Acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), and polycarbonate (PC) are common building materials used in FDM. FDM can only produce plastic items almost exclusively due to
constraints in the materials and printing technique. This suggests that post-processing, such as the metallization of conductors, is necessary to produce metallic antennas. Recently, FDM has made use of a unique material known as “Electrifi” that enables the printing of antenna structures in a single step. It is composed of a special metal-polymer combination composed of non-hazardous biodegradable polyester and copper and has better conductivity than regular filaments [70]. However, the weight of the Electrifi filament is approximately 2 and 2.35 times heavier than PLA and ABS filaments, respectively [75]. The silver conductive spray is approximately 10 times more conductive than Electrifi. Therefore, when it comes to achieving low weight and high conductivity, utilizing a thermoplastic filament for printing the object and then coating its surface with silver spray is a better option than using the Electrifi filament [76].

Table 2.1 provides a summary of the additive manufacturing techniques. In this thesis, the extrusion based FDM method will be used to fabricate the proposed antennas. The reason for selecting FDM is that it offers several advantages, such as the ability to use a wide range of materials like lightweight thermoplastics, which helps in achieving the desired low-mass characteristic. Moreover, the FDM process is very cost-effective compared to other techniques like photopolymerization.

2.5.2 Additive Manufacturing of Antennas

Antennas have been made from a variety of materials, including thermoplastics, resins, ceramic materials, and metal powder. These materials listed above have advantages and disadvantages. Some are minor and others are significant. In general, 3D printed antennas can be divided into the following groups based on the materials used in their production [70]:

A. Metallic antennas printed directly with conductive materials or printed with dielectric materials and then metallized.
B. Ceramic antennas
C. Polymer antennas
D. Composite material antennas (ceramic polymer matrices)
E. Multi-material integrated antenna (dielectric and conductor materials)
Table 2.1 A summary of the addictive manufacturing techniques

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<tr>
<td>Two-photon polymerization</td>
<td>UV curable resins</td>
<td>Nanometer resolution</td>
<td></td>
<td>Limited mechanical properties</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Relatively poor surface finish</td>
</tr>
<tr>
<td>Lamination</td>
<td>Selective deposition lamination</td>
<td>Paper Metal foil Plastic film</td>
<td>Inexpensive Excess materials can be recycled</td>
<td>Poor strength Requires post-processing</td>
</tr>
<tr>
<td>Powder based</td>
<td>Selective laser sintering</td>
<td>Metal powders Ceramic powders</td>
<td>Does not require support structures</td>
<td>Porous surface Poor surface finishes May require long heating and cooling</td>
</tr>
<tr>
<td>Extrusion</td>
<td>Fused deposition modeling</td>
<td>Thermoplastics Clay</td>
<td>Vast range of materials Very cost-effective Availability of desktop scale printer</td>
<td>Requires support structures Grainy appearance</td>
</tr>
</tbody>
</table>

A. Direct Metal Printing

A conducting element is needed in many traditional antenna layouts in order to connect the input port to a signal generator and produce resonance. Although poor conductors work well for 3D printed electrical circuits, their large losses make them unsuitable for use in antenna applications. Printed metallic antennas are an area that deserves further investigation and advancement. Additionally, metallic 3D printed components can provide greater mechanical robustness and less electrostatic discharge in comparison to dielectric antennas. Utilizing direct metal laser sintering
(DMLS) or SLM, pure metallic antennas can be produced directly from titanium, steel, or aluminum [70].

B. Metallization after 3D printing

An alternate and less expensive technique is to print metallized antenna components using regular filament (FDM technique) or resin (SLA), then coat them with conductive materials. The metallized prototype should, in theory, function identically to the metal counterpart once it has been metallized with a metal-like smooth coating thicker than the skin depth at the required operating frequency. With the use of this technique, antenna technologies can incorporate finely detailed and exact 3D designs related to additive manufacturing procedures. In comparison to pure metal antennas, the approach offers further weight advantages and a material cost that is much lower [70].

There are four common metallization techniques which includes vacuum metallization, electroplating, jet metal (JMT), and conductive spray. Vacuum metallization is a process where metals are evaporated and condensed on a 3D object in a vacuum chamber. On the other hand, electroplating involves submerging a conductive 3D-printed object in a metallic salt solution and introducing a current source between the object (cathode) and the solution (anode). Metallization occurs due to the attraction of the metallic salt to the 3D-printed part [78]. Although both techniques are effective in depositing uniform metal layers, they are more expensive compared to other methods.

Jet metal (JMT) is a spray coating technique that uses two spray guns at room temperature and ambient pressure to coat a thin, smooth layer of silver (Ag) metal on a substrate. The JMT technique has been reported to produce the best performance at a lower cost compared to the vacuum metallization and electroplating techniques [79]. Conductive spray is the most cost-efficient of all the techniques mentioned and the easiest to implement. It involves manually spraying (by hand) several layers of metal in aerosol form on a 3D-printed object [70], [78], [79].

C. Polymer Antennas

Since polymers can be printed more easily than conductive materials, they are not substituted by other materials in the manufacture of antennas. According to [70], the best technique for producing dielectric antennas like lenses and dielectric resonator antennas (DRAs) is 3D printing. Complex
structures like Luneburg lens (LL) and DRAs can be printed using high-resolution SLA and polyjet technology, which is used in the production of polymer antennas. The creation of lightweight antennas that satisfy 5G communication system specifications is another benefit of employing polymers. The mechanical resilience of polymer antennas is, however, less than that of metallic antennas. The polymer components need to be integrated into conductors in multiple situations. The performance of the antennas is impacted if the combination is of low quality [70], [80], [81].

D. 3D Printed Ceramic Antennas

Ceramic materials can offer a greater range of dielectric permittivity and more stable mechanical characteristics as compared to polymers [82]. High resolution ceramic SLA (CSLA) is used in ceramic antenna manufacture to enable the creation of complex structures. Furthermore, near-zero temperature coefficient of resonant frequency, high microwave quality factor, and low dielectric loss ceramic materials have been developed. Using these materials permits the potential integration and miniaturization of 5G radio frequency components. Alumina, bioactive glasses, and zirconia are a few examples of ceramic materials that have been used for fabricating 3D printed ceramic antennas [83], [84].

E. Composite Material Antennas

High-performance industries have been revolutionized by composite materials because of their remarkable adaptability, low weight, and adaptable qualities [85]. Glass fiber reinforced polymer composites and carbon fiber reinforced polymer composites are two examples of composite materials [70]. The aerospace industry makes extensive use of carbon fiber reinforced polymer composite structures due to their high specific stiffness, strength, excellent corrosion resistance, and exceptional fatigue performance. Glass fiber-reinforced polymer composites, on the other hand, are extensively utilized in a variety of 3D printing applications and have a wide range of prospective uses because of their excellent performance and affordability. Fiberglass has a low coefficient of thermal expansion and a high thermal conductivity [85], [86].

2.5.3 Post Processing Methods

Many industries have shown signs of increased interest in the use of additive manufacturing (AM) methods, but there has been little adoption of this technology in terms of larger-scale
The primary cause of this is the inadequacies in current additive manufacturing processes concerning the achievable geometrical accuracy and surface integrity of the workpiece. Generally, parts have poor surface roughness, stair-step effects on surfaces, balling, detrimental residual stresses, and low dimensional precision. To achieve functional tolerances and surface integrity requirements, post-processing methods are frequently utilized for 3D-printed components [87].

The first post-processing step is the support removal [69]. Supports used for AM can be classified into two categories: soluble and insoluble supports. Soluble supports can be easily removed from the printed parts by dissolving them in a solvent that will not cause any damage to the object, an example of these include high-impact polystyrene (HIPS) and polyvinyl alcohol (PVA) used as supports for ABS and PLA respectively. On the other hand, insoluble supports must be removed by hand, using tools such as cutters and pliers.

The next post-processing step involves smoothing the surface of the 3D printed part either chemically or mechanically as shown in Figure 2.13. Mechanical smoothing involves processes like sanding where several grit sizes of sandpapers are used to polish the surface of the object in different phases. While this method is effective, it can be very time-consuming. Acetone-vapor polishing used for ABS plastics is the most common chemical polishing process. In this process, the object is exposed to acetone vapor for a duration of time, and the layer lines on the outer surface melt and smoothen out leaving a shiny finish. This process can be difficult to control and can lead to uneven removal of material. After the polishing step, depending on the application of the 3D printed part, the object can be primed, painted, metallized, or combined with other parts [88].

Figure 2.13 The before and after polishing of a 3D-printed object [87].
2.5.4 Advantages of Additive Manufacturing

Cost Efficiency: When it comes to additive manufacturing, the cost of producing hundreds of parts is almost the same as the cost of one part. For example, for the FDM technique, one spool of thermoplastic filament can produce multiple 3D-printed pieces without additional cost. This is not the case for traditional fabrication techniques which usually requires an expensive tooling stage for the mass production of objects. The conventional manufacturing and assembly phase necessitates high labor and equipment setup expenses. With 3D printing, these expenses are significantly decreased, if not completely removed, as it involves less manual labor, does not require changing tools, and takes less time to assemble [89].

Fabrication of Complex Designs: One of the top advantages of AM is that it can create pieces that were previously impossible to manufacture. AM usually requires a single machine and process to create the complete part of a model from start to end. It is effective in building complex geometries that are impractical, expensive, or impossible to construct with other techniques [86]. Subtractive manufacturing on the other hand will require multiple steps and tools to create the same design.

Wide range of materials: AM is also capable of using a wide range of materials, including metals, composites, ceramics, and numerous types of plastic. The material used depends on the type of AM method employed. Since they have been studied the most, and have been used for the longest, plastics are the most widely used materials. AM can work with a variety of materials, and scientists, and engineers are also discovering new ways to modify the properties of these materials through the AM process. Using some of the latest advancements in freeform manufacturing, it is possible to fuse metal and ceramic to produce composites with improved wear characteristics [86], [90].

AM has also allowed for the creation of lighter-weight parts because of its wide range of usable materials. For example, a 70% reduction in the mass of the short backfire antenna was achieved by employing the FDM additive manufacturing technique using thermoplastics instead of conventional aluminum metal [60], [61].

Time Efficiency: Most conventional fabrication processes take days compared to AM techniques which complete the whole fabrication process within a few hours. The injection molding technique
usually requires the creation of molds to fabricate parts. This process alone can take 1-2 months. 3D printing techniques eliminate the expensive tooling stage [89].

**User Friendly Machinery:** When compared to traditional equipment used for making antennas, most 3D-printers are very easy to use. To operate machine tools, one needs to attend a technical school to learn how to use them and then practice improving their skills. On the other hand, using a 3D printer is a relatively straightforward process and usually only requires reading the user manual to be able to operate it. Entry-level 3D printers are available for hobbyists at a reasonable price.

**Sustainability:** AM only produces the minimum amount of support structure required for building an object, in contrast to subtractive manufacturing, which removes waste material to expose a product. Auxiliary tools, equipment, and coolants are frequently needed for conventional machinery, which uses energy and produces waste and pollutants. Compared to conventional machines, AM requires less supporting equipment, which means it uses less resources and energy. Additionally, parts can be produced by smaller manufacturers located closer to users because these auxiliary tools and equipment are not required for production, which lowers transportation costs and associated emissions [91].

### 2.5.5 Challenges of Additive Manufactured Antennas

**Resolution:** The resolution of 3D printed parts can pose a challenge for high-frequency antennas in the mmWave and THz range with complex and intricate structures. Small errors in fabrication have a significant impact on the antenna’s performance because the resonance frequency is dependent on the antenna’s structure. As the frequency increases, the dimension of the antenna gets smaller which worsens this issue. Hence, the production processes for mmWave/THz antennas must meet strict requirements for precise geometrical features.

**Surface Roughness:** The surface roughness of the 3D-printed structure presents another significant manufacturing challenge for antennas. In terms of increased conductor loss, a rough surface can significantly lower the electromagnetic performance. In [92], two 3D-printed antennas with different surface roughness values were compared, the antenna with the higher surface roughness had higher loss and lower gain values. Higher surface roughness is also the main factor
in antenna loss and can have a detrimental effect on the propagation of electromagnetic waves. The impact of surface roughness on the antennas’ performance is greater for mmWave and THz frequencies. As a result, it is of the utmost importance to minimize surface roughness in 3D-printed components. Additionally, the technique employed affects surface roughness. Therefore, when producing an RF component, it is important to consider the type of 3D printing technology to be used. To get a smoother surface finish after printing, a post-polishing step is required. For more intricate components, polishing the interior of the structure might be challenging. The cost is also increased overall by the high expense of some polishing processes. Improving the surface roughness is therefore one of the difficulties in the 3D printing of high-frequency antennas.

**Material Properties:** Considering the material used to build a structure is crucial in the design and production of antennas. The efficiency of the antennas depends on the electromagnetic characteristics (EM) possessed by the materials. As of right now, to our knowledge, no commercially accessible material used in 3D printing techniques has been created for electromagnetic purposes. Rather, many of these materials are chosen or created solely based on their mechanical characteristics. The lack of materials with the required EM properties limits the usage of 3D-printed materials for creating microwave components. Thus, there is an urgent need to produce materials with the appropriate EM characteristics [70], [93].

In the case of conductive filaments, electrical conductivity is a very important property. The low conductivity of the conductive filaments and inks that are presently available causes larger losses and has a major influence on antenna performance. For instance, in [94] two horn antennas working at 12 GHz were 3D printed. ProtoPasta, a conductive PLA, was used to directly print one, while the other was fabricated using a standard filament and coated with copper tape. The second horn antenna obtained better gain and bandwidth measurements when compared to the prototype printed with ProtoPasta which had a lower gain and an efficiency of 35%.
3. Mass Reduction Techniques for Short Backfire Antennas

3.1 Introduction

This chapter presents relatively new methods that use structural perforations and additive manufacturing to reduce the mass of a short backfire (SBF) antenna fabricated by traditional metal machining techniques. To develop the first antenna design, the FDM additive manufacturing technique was investigated to create a lightweight prototype which was then metallized. A 70% reduction in mass was achieved using this method compared to the conventional fabrication technique which employs solid aluminum metals. To explore the effects of the manufacturing process, several parametric simulation studies were conducted which demonstrated that there was no significant difference in performance. The conductivity of the metal paint and surface roughness due to the 3D printing process accounted for the majority of the errors. To minimize the mass further, a second antenna with structural perforations in the rim was designed and fabricated using a 3D printer. Parametric studies were performed to characterize the impact of different sizes and shapes of perforations, the effect of surface roughness on the antenna and to optimize both performance and mass reduction. Prototype antennas were fabricated and tested. The masses of the 3D-printed and the perforated 3D-printed antennas were significantly reduced by 70% and 80%, respectively compared to the aluminum prototype of the same design. The method’s efficacy was shown by the excellent agreement between the initial design, simulation, and measurement results. Table 3.1 provides an overview of the proposed antenna’s design specifications. These performance metrics were developed using design specifications from current C-band remote sensing systems and by comparing them to other designs that are already published in the literature. The SBF antennas in this study were designed to target the C-band (4–7 GHz) with a center operating frequency of 5.5 GHz, which corresponds to a wavelength of \( \lambda_0 = 54.54 \) mm in free space. The realized gain of the antenna must be at least 14 dBi and its impedance bandwidth must be at least 500 MHz with an operating frequency of 5.5 GHz for it to function well. The goal of this study is to get the antenna’s mass down to less than half of the previously designed aluminum prototype.

Materials in this chapter have been published in:

In chapter 3, the following sections will be covered: Section 2 presents the design of the 3D printed SBF antenna and discusses parametric studies on the expected effects of the fabrication process such as an increase in surface impedance and surface roughness. The section also includes information on the fabrication process as well as the measurement results.

In Section 3, a new antenna design, called a “perforated SBF antenna,” is introduced. This design aims to reduce the mass of the antenna by employing the 3D printing process along with perforation techniques. Simulation studies were conducted to analyze the impact of different perforation sizes on the antenna’s gain, bandwidth, and cross-polarization ratio performance. The fabrication process of the perforated SBF antenna is presented along with the measured results.

### 3.2 3D Printed SBF Antenna Design Concept

In this section, a prototype of an aluminum waveguide-fed short backfire (SBF) antenna was investigated to see the potential advantages of fabricating it with additive manufacturing techniques. The aluminum prototype is a modified version of the classic SBF antenna and is shown in Figure 3.1. This specific antenna was originally presented in [17]. It consists of a main reflector, a sub reflector, a rim, and a choke. The choke was the main modification that was used to...
previously enhance the antenna performance. The addition of a choke increased the gain by constraining the surface current within a smaller area, leading to a higher surface current density.

Figure 3.1 Geometry of the modified SBF antenna.

Figure 3.2. Top view of the SBF antenna.
As mentioned in the background chapter, the layer-by-layer printing process during 3D printing introduces surface roughness to the printed part. The flow dynamic of molten plastics often limits the resolution of FDM 3D printers compared to SLA printers that produce better quality resin-based objects with higher resolutions since they are not affected by this factor. This roughness can impact the performance of high-frequency antennas as the surface roughness values begin to
approach the same range as the wavelength, resulting in the degradation of performance. At high frequencies, surface irregularities and defects cause changes in the conductor’s electrical characteristics, which affect its effective conductivity as shown in equations 3.1 – 3.4. These equations show the relationship between effective conductivity $\sigma_{\text{eff}}$, the 3dB bandwidth and surface roughness $h$. Where $\sigma_0$ is the bulk conductivity (S/m), $\delta_0$ is the skin depth with an ideal surface (no surface roughness) in meters, $Q$ is the quality factor with a rough surface, and $Q_0$ is the quality factor with an ideal surface.

\[
\sigma_{\text{eff}} = \frac{\sigma_0}{\left(1 + e^{-\left(\frac{\delta_0}{2h}\right)^{1.6}}\right)^2}
\]  
(3.1)

\[
Q = \frac{Q_0}{1 + e^{-\left(\frac{\delta_0}{2h}\right)^{1.6}}}
\]  
(3.2)

\[
3\,\text{dB\,BW} = \frac{f_0}{Q}
\]  
(3.3)

\[
3\,\text{dB\,BW} = \frac{f_0\left(1 + e^{-\left(\frac{\delta_0}{2h}\right)^{1.6}}\right)}{Q_0}
\]  
(3.4)

From the equations above, an increase in the surface roughness of the antenna’s conductive surface leads to a decrease in its effective conductivity and quality factor, which in turn increases the 3dB bandwidth. As a result of the decreased conductivity, there is an increase in the signal loss (gain loss) and dispersion which is one of the prominent effects of surface roughness. Simulating the effects of various surface roughness values on the SBF antenna’s performance is therefore necessary to mitigate them.

All the modeling and simulations in this thesis was performed using Ansys high-frequency structure simulator (HFSS) Electronics Desktop 2021 R2©. Ansys HFSS is an EM solver software that is used in the design and simulation of high frequency electronics like RF antennas. HFSS uses the finite element method (FEM) technique, which involves dividing the structure into smaller
divisions known as finite elements. Each of these subdivisions are then solved using Maxwell’s Equations. Depending on the antenna design and the smallest detail, the mesh size can be reduced to achieve more accurate results.

There are two major steps involved in this design process. As the antenna was made using a thermoplastic material, Acrylonitrile Butadiene Styrene (ABS) was used to model the structure. ABS is a lightweight thermoplastic commonly used in 3D printing that has a high tensile strength and a remarkable resistance to corrosion and physical impacts which makes it capable of withstanding harsh conditions. Since ABS material is not found in the HFSS material library, a material with a relative permittivity of 2.8 and a loss tangent of 0.005 [95] was created to approximate the ABS plastic material. After completing the 3D printing process, the antenna was metallized using the MG chemicals super shield nickel conductive coating. To model this metal spray coating in HFSS, an impedance boundary condition was applied to the entire surface of the 3D object as shown in Figure 3.5. Typically, the metallic coating is simulated with an impedance boundary condition, while the surface roughness is simulated separately using a layered boundary condition, which allows for easy variation of the surface roughness value. As it is not feasible to simulate two boundary conditions simultaneously, and since surface roughness has a direct impact on the surface impedance, the surface roughness and metal coating were modeled together using the impedance boundary condition. Surface roughness affects the flow of current on a conductor’s surface which results in an increase in ohmic loss leading to a higher effective surface resistance compared to the case with no roughness. This loss increases with frequency since the wavelength becomes shorter and ranges closer to the size of the surface roughness [96].
3.2.1 Antenna Performance Analysis (HFSS) simulation

The dimensions of the SBF antenna used to simulate its performance are provided in Table 3.2. Various surface impedances were studied to investigate the effect of the rough surface resulting from the construction process on the antenna’s performance. The results of two different scenarios were also compared: one where the antenna was completely coated, and another where the coating only applied to the inside walls of the antenna. Surface resistance values of 0.6/sq, 3/sq, and 10/sq were used to generate simulated plots. The nickel conductive coating’s surface resistance of 0.6 Ω/sq [97] was employed as the lowest surface resistance without accounting for the surface roughness resulting from the 3D-printing process. The aluminium prototype showed a gain loss of roughly 0.6 dB between the simulation and measured result, this same gain loss was obtained between the simulation and measured result of the 3D printed antenna using the 3 Ω/sq surface impedance case, hence why this impedance value was added in the simulation study. The results of the 10 Ω/sq were also included to demonstrate the effect of a much larger surface resistance on the antenna’s performance.
Table 3.2 Dimensions of the simulated 3D printed SBF antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Diameter of the main reflector</td>
<td>120.00</td>
</tr>
<tr>
<td>D&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Diameter of the sub-reflector</td>
<td>38.18</td>
</tr>
<tr>
<td>H&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Height of the rim</td>
<td>32.73</td>
</tr>
<tr>
<td>H&lt;sub&gt;s&lt;/sub&gt;</td>
<td>Height of the sub-reflector</td>
<td>38.48</td>
</tr>
<tr>
<td>H&lt;sub&gt;wg&lt;/sub&gt;</td>
<td>Height of the waveguide</td>
<td>54.55</td>
</tr>
<tr>
<td>R&lt;sub&gt;choke&lt;/sub&gt;</td>
<td>Distance between the rim and outer diameter of the choke</td>
<td>5.46</td>
</tr>
<tr>
<td>d&lt;sub&gt;choke&lt;/sub&gt;</td>
<td>Depth of the choke</td>
<td>16.06</td>
</tr>
<tr>
<td>W&lt;sub&gt;choke&lt;/sub&gt;</td>
<td>Width of the choke</td>
<td>16.06</td>
</tr>
<tr>
<td>a</td>
<td>Length of the waveguide feed</td>
<td>40.39</td>
</tr>
<tr>
<td>b</td>
<td>Width of the waveguide feed</td>
<td>20.19</td>
</tr>
<tr>
<td>W&lt;sub&gt;iris&lt;/sub&gt;</td>
<td>Width of the iris</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Results for the peak realized gain were computed for the different surface impedance values. Table 3.3 summarizes the gain results. The realized gain gradually decreased from 16.25 dBi to 15.4 dBi (0.87 dB gain loss) as the surface impedance increased from 0.6 Ω/sq to 10 Ω/sq. Compared to when only the inner walls were coated, the performance of the fully coated antenna was marginally improved. The plot of the realized gain as a function of frequency comparing the aluminium prototype and the 3D-printed prototypes with surface roughness (SR) values of 0.6 Ω/sq, 3 Ω/sq, and 10 Ω/sq is shown in Figure 3.6. The gain dropped as the SR value increased, as would be expected based on the prior finding. The peak gain for the different cases were obtained at 5.6 GHz. The aluminum prototype had the highest peak gain of 16.7 dBi at 5.5 GHz, followed by the 3D-printed prototype with SR values of 0.6 Ω/sq, 3 Ω/sq, and 10 with peak gain values of 16.5 dBi, 16.1 dBi, and 15.6 dBi, respectively. The gain bandwidth of operation that satisfied the 14 dBi requirement extended from 4.8 to 5.75 GHz (950 MHz) for the aluminum antenna and from 4.8 to 5.75 GHz (950 MHz), 4.9 to 5.8 GHz (900 MHz), and 5.0 to 5.7 GHz (700 MHz) for the 0.6 Ω/sq, 3 Ω/sq, and 10 Ω/sq 3D-printed prototypes, respectively. This proved that reducing the surface roughness increased the peak gain and the gain bandwidth as confirmed by equations 3.1-3.4.
Table 3.3 Effect of the surface impedance on the gain of the SBF antenna.

<table>
<thead>
<tr>
<th>Surface Impedance (Ω/sq)</th>
<th>Gain (dBi)</th>
<th>Gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Entire Body Coated</td>
<td>Inner Walls Coated</td>
</tr>
<tr>
<td>Aluminum</td>
<td>16.70</td>
<td>N/A</td>
</tr>
<tr>
<td>0.6</td>
<td>16.45</td>
<td>16.25</td>
</tr>
<tr>
<td>1</td>
<td>16.36</td>
<td>16.20</td>
</tr>
<tr>
<td>3</td>
<td>16.05</td>
<td>16.00</td>
</tr>
<tr>
<td>5</td>
<td>15.91</td>
<td>15.80</td>
</tr>
<tr>
<td>7</td>
<td>15.78</td>
<td>15.65</td>
</tr>
<tr>
<td>10</td>
<td>15.58</td>
<td>15.40</td>
</tr>
</tbody>
</table>

Figure 3.6 Simulated realized gain plots ($\varphi = 0^\circ$) comparing the aluminum prototype and the 3D-printed prototypes with surface roughness (SR) values of 0.6 Ω/sq, 3 Ω/sq and 10 Ω/sq.
Figure 4 shows the simulated worst-case cross-polarization ratio curves for the 3D-printed and aluminium antenna designs. The aluminium sample had a minimum cross-polarization ratio of 24 dB, while the 3D-printed prototypes with 0.6 Ω/sq, 3 Ω/sq, and 10 Ω/sq had minimum cross-polarization ratio values of 24.5 dB, 24 dB, and 22 dB, respectively, at 5.6 GHz. It can be inferred that increasing the surface roughness of the antenna had very little effect on the cross-polarization ratio and the plots of the aluminium and the 3D-printed antennas with different SR values were in close agreement.

The simulated reflection coefficient results for the aluminum and 3D-printed prototypes are provided in Figure 3.8. This figure illustrates how the SBF antenna’s impedance bandwidth improved with the increasing surface resistance. The aluminum prototype was found to have a 10 dB impedance bandwidth of 1.8 GHz (37.5%), whereas the 3D-printed antenna had three different bandwidths: 1.84 GHz (38.5%), 1.86 GHz (39%), and 1.92 GHz (40%) for SR values of 0.6 Ω/sq, 3 Ω/sq, and 10 Ω/sq, respectively. Equations 3.1-3.4 demonstrate a direct relationship between impedance bandwidth and surface roughness, which supports the increase in impedance bandwidth with increasing roughness.

Figure 3.7 Simulated worst-case cross-polarization ratio at φ = 45°, comparison of the aluminum prototype and the 3D-printed prototypes with surface roughness (SR) values of 0.6 Ω/sq, 3 Ω/sq and 10 Ω/sq.
Figure 3.8 Simulated reflection coefficient plots for the aluminum and 3D-printed prototypes.

The surface current distribution of the 3D printed SBF antenna is given in Figure 3.9. All the components of the antenna contribute to the radiation of the antenna. The highest current density is located closest to the waveguide feed therefore that is the primary radiation region. On the other hand, the rim and the choke regions can be seen to have the lowest current density. This current distribution characteristic of the SBF antenna will be taken advantage of in the next section where the perforation technique is applied.

Figure 3.9 Simulated surface current distribution of the 3D printed SBF antenna.
It was expected that the thickness of the metal layer on the surface of the ABS material would vary slightly due to the manual application of the coating. To investigate the impact of this thickness variation on the functionality of the 3D-printed SBF antenna, the main reflector’s diameter gradually decreased from 120 mm to 119 mm in steps of 0.1 mm while using a surface impedance of $3\Omega/\text{sq}$. The results of this variation on the peak realized gain and reflection coefficient are shown in Figure 3.10 and Figure 3.11. The results reveal that the antenna’s performance remained unaffected by the thickness fluctuation, as the gain remained constant at $\pm0.1$ dB, as shown in the results. The reflection coefficient results did not change within this range as well.

A summary of the results of the study performed in this section is provided in Table 3.4. The performance of the aluminum SBF antenna and the 3D-printed SBF antenna are compared as it relates to surface impedance and roughness. It was observed that although the reflection coefficient ($S_{11}$) increased with increasing impedance value, these changes were not very significant; on the other hand, the gain dropped significantly as the surface roughness and resistance rose. Thus, it was critical to minimize the surface roughness. This problem is addressed in the next chapter.

![Figure 3.10 Simulated effect of the metal coating layer variation on the peak realized gain of the SBF antenna.](image-url)
3.2.2 Antenna Measurement

The realized gain, impedance bandwidth (reflection coefficient), and cross-polarization ratio performance are the major antenna parameters that will be focused on and measured in this thesis. The reflection coefficient is measured using a vector network analyzer while the gain and cross polarization results can be obtained from the far-field radiation measurement. This section gives a brief explanation of these measurement procedures.
Reflection coefficient measurement: The reflection coefficient also known as the return loss of a device describes how much electromagnetic waves is reflected back to the source from the input due to impedance mismatch between the signal generator and the input of the antenna.

The step-by-step process involves:

1. Calibration: The first step in measuring the return loss of an RF device such as the SBF antenna is to calibrate the device. The goal of calibration is to eliminate systematic errors from the instrument hardware at the frequencies needed for the measurements, while also accounting for any accessories that may have been added to allow for the performance of certain experiments [98]. Taking this step will ensure accurate measurements. For the measurement of the antennas presented in this thesis, I used the two-port Keysight N7555A electronic calibration (ECal) module provided in Figure 3.12. Unlike the traditional calibration process that requires connecting multiple known loads to the vector network analyzer (VNA) ports, the ECal module requires just one connection. Therefore, the process is faster and reduces errors due to operator. It works by transferring factory calibration to the VNA [99].

![Figure 3.12 Keysight N7555A electronic calibration module.](image)

2. Connection and Configuration

The Keysight N5224B VNA was used to measure the return loss of the SBF antennas. Although the device has two ports, only port 1 of the VNA is used because the antenna being tested has only...
one port. The measurement setup is provided in Figure 3.13 with the waveguide adapter of the SBF antenna connected to port 1 of the VNA. The VNA also has to be configured to show results within the desired frequency.

3. Measure and Save Data

After connecting the antenna to the VNA and configuring the desired measurement settings, the RF power supply of the VNA should be turned on to supply the antenna with RF signal and measure the reflected signal which is usually provided in negative decibels (dB). The higher the decibel value, the better the impedance matching of the antenna’s input to the VNA port. Once the measurement is done, the data can be saved and exported for more processing.

![Figure 3.13. Return loss measurement using the vector network analyzer.](image)

**Far-field measurement:** The far-field measurement for the short backfire antennas was done at the University of Manitoba’s compact antenna test range (CATR) facility shown in Figure 3.14. The CATR measures an antenna’s far-field in an anechoic chamber. The anechoic chamber is basically a room with walls covered in RF absorbers to prevent electromagnetic wave reflections. The CATR is capable of transforming spherical waves to planar waves at a relatively short distance,
therefore creating a far-field condition in smaller spaces [100]. The University of Manitoba’s CATR is a single paraboloidal reflector CATR design where there is a single reflector illuminated by a single feed that is offset by an angle from the direction of the reflected waves. The horn antenna with known measurements is used as the feed antenna while the reflector has a serrated edge. This serrations are to reduce wave diffraction around the reflectors edges [32].

The antenna under test (AUT) is placed on a positioner system that is moved both in the azimuth and the horizontal planes and also rotated around an axis within -90° to 90°. The AUT measures the reflected EM wave, and the radiation pattern is generated depending on the configuration. The E-plane radiation field and its cross-polarization is measured by setting the polarization to 0° and then rotating the azimuth plane from -90° to 90°. The H-plane follows the same except the polarization is set to 90°. The worst-case polarization ratio is measured at a polarization of 45° while the antenna is rotated in azimuth plane from 45° to 135°.

Figure 3.14. University of Manitoba’s compact antenna test range (CATR) facility.
3.2.3 Fabrication and Testing of the 3D-Printed SBF Antenna

The 3D-printed SBF antenna was fabricated at the University of Manitoba’s machine using the Airwolf AXIOM 2 3D printer shown in Figure 3.15a. Using two independently controlled, high-temperature nozzles, the AXIOM 2 is designed for multi-material 3D printing. It is also capable of handling a variety of materials, including nylon and polycarbonate, due to its ability to withstand temperatures as high as 315 °C (599 °F). This 3D printer operates using the FDM technique with thermoplastic filaments. To print the SBF antenna, the design file for the antennas was exported from the HFSS software in the “iges” format and then converted to the “stl” format using the AutoCAD software. The antenna was then printed using ABS filament and then coated by hand using the MG chemicals super shield nickel conductive coating (aerosol) shown in Figure 3.15b to metallize the antenna and create a conductive surface. The cured conductive spray has the following properties: a resistivity of $7.6 \times 10^{-3} \Omega \cdot \text{cm}$, a surface resistance of 0.6 $\Omega/\text{sq}$, and a service temperature range of -40 – 120 °C. It provides an effective EMI/RFI shielding over a broad frequency range and strong corrosion resistance [97]. The coated 3D printed SBF antenna prototype is shown in Figure 3.16.

A foam material was used to support the sub-reflector at the required distance from the main reflector. The sub-reflector was then attached on top of the foam at the center. This option was considered because the foam has a dielectric constant ($\varepsilon_r$) of 1.05. Since the value is very close to the relative permittivity of air ($\varepsilon_r = 1$), the performance of the antenna is not affected by this dielectric structure. To fully assemble the antenna as shown in Figure 3.17, the 3D printed part was connected to the WR159 waveguide antenna feed that has a frequency band of 4.9 to 7.05 GHz which falls within the operating frequency of the prototype SBF antenna.

The Keysight PNA Vector Network Analyzer (N5224B VNA) was used to measure the $S$-parameter (S11) of the 3D-printed antenna, while the far-field radiation pattern was obtained at the University of Manitoba’s Compact Antenna Test Range. These measurements were carried out to validate the performance of the antenna design and to ensure that all requirements are met.
Figure 3.15. (a) Airwolf AXIOM 2 3D printer, (b) MG Chemicals super shield nickel conductive coating.

Figure 3.16. Fabricated 3D-printed antenna: (a) top view; (b) bottom view.
Figure 3.17. Fully assembled 3D-printed antenna showing the foam material and the waveguide feed.

In Figure 3.18, the simulated S11 results for the 3D printed antenna is compared to the measured results for the aluminum and 3D printed prototypes. Both measured results exhibit some interference in the line having three notches compared to the simulated results with only two notches, this interference is because of the behavior of the waveguide antenna that was used as the feed. The S11 results of the waveguide antenna alone showed multiple notches between 4-5 GHz [17] which had a negative effect on the SBF antenna result. This is why an inductive iris was added to the design, to make sure that this interference does not affect the impedance bandwidth of the antenna. The pattern of the S11 results of the solid 3D-printed SBF antenna, and the aluminum antenna showed good agreement; the measured impedance bandwidths were 1.38 GHz (27.7%) and 1.35 GHz (27.3%), respectively. The decrease in the frequency range and impedance bandwidth of the measured results compared to the simulated results is partly due to the waveguide.
Figure 3.18. Measured S11 plots for the 3D-printed antenna compared to the aluminum prototype.

Figure 3.19a displays the results of the radiation pattern measurements and simulations for the 3D-printed SBF antenna. The simulated peak gain, which considered the effects of the foam insert and used a surface impedance of 3 $\Omega$/sq, was 15.63 dBi, compared to the measured peak gain of 15 dB (0.63 dB gain loss). Based on previous experiments, it was discovered that there is a loss of approximately 0.6 dB gain due to insufficient bonding between the waveguide flange and the main reflector. Additionally, there is also some insertion loss caused by the connection between the waveguide port and the coaxial cable [17].

Using Ludwig’s third definition, the measured cross-polarization ratio was determined at 5.5 GHz from Figure 3.19b. The worst-case cross-polarization ratio of the 3D-printed antenna was 19.9 dB, which was obtained at $\varphi = 46^\circ$ and $\theta = 38^\circ$. This was very close to the aluminum prototype’s worst-case cross-polarization ratio of 20.9 dB that was measured.
A gain loss of almost 0.7 dB was observed when comparing the measured peak gain of the aluminum prototype (15.7 dB) to that of the 3D-printed SBF antenna (15 dBi). The primary reason for this gain loss can be traced back to the layer-by-layer printing process, which resulted in some surface roughness on the 3D-printed antenna’s surface (these layers can be seen in Figure 3.16 by visual inspection), the surface of the printed antenna felt less smooth compared to that of the aluminum metal. Another factor contributing to the gain loss is the imperfect metallization process. The literature has shown equivalent losses like these for horn antennas made with alternative 3D printing + metallization methods. The problem of surface roughness will be addressed in chapter 4 and future work to improve antenna performance.
3.3 Perforated 3D Printed Antenna

3.3.1 Design Concept

The second antenna design in this chapter for mass reduction is the perforated short backfire antenna. The perforation technique is a straightforward method that reduces weight by purposely making a sequence of sub-wavelength slots in the antenna, which are substantially smaller than the wavelength of the antenna \( \lambda_0 = 54.54 \text{ mm} \). The transmitted electromagnetic wave is not expected to radiate from the holes theoretically as their diameters are less than \( \lambda_0 \), hence they have little to no impact on the antenna's performance. However, from extensive simulations, it was observed that there is a limit to how large these perforations can be before they started affecting the performance of the antenna negatively even while being much less than a wavelength in size. Therefore, it is very important to study different sizes, shapes, and arrangements of the perforations.

During the simulation studies of the previous antenna design, the surface current density was highest in the primary reflector and lowest in the rim. Therefore, only the antenna’s rim was perforated, as this would cause less of a degradation to the antenna’s field and overall performance. Some attempts were made to also perforate the main reflector, but this caused a substantial gain loss. This design is the same as the previous design except for having a 3x37 array of circular holes in the rim of the antenna.

After several studies on different shapes, sizes, and positioning of the slots on the antenna’s rim based on this technique, the waveguide-fed perforated SBF antenna shown in Figure 3.20 was proposed.
The design and simulations were done using Ansys HFSS. The process of modeling the perforated antenna illustrated in Figure 3.21 is as follows:

1. The antenna rim was modelled as a rectangular sheet with a width equal to its height \((W = Hr)\) and a length equal to the rim’s perimeter \((L = 2\pi Dm)\).

2. A periodic arrangement of circles with equal radius and distance between them is created in the same plane as the rectangular sheet. This can be achieved by designing one circle and using the “duplicate along line” function in HFSS to repeat it along the y and z directions.

3. To proceed, the rectangular sheet was modified by subtracting the circles from it. This was achieved by selecting the rectangular sheet first and then selecting all the circular sheets as a group, before using the ‘subtract’ function - a modeling tool in HFSS - to create holes in the sheet.

4. The perforated rectangular sheet was then wrapped around the original unperforated design so that it can form the cylindrical shape of the rim. The unperforated rim was deleted after this, leaving the perforated rectangular sheet as the new rim.

5. The final step was to thicken this new rim and then unite it with the rest of the antenna.

The goal for this study is to increase the size of the holes as much as possible to maximize the mass reduction while maintaining the same performance as the unperforated design. Different circle radii were simulated to investigate the effect of the perforations on the performance of the
antenna. During the investigation process all other antenna parameters were kept constant. The optimized dimensions of the perforated SBF antenna are given in Table 3.5.

(a)

Modelling the rectangular sheet

(b)

Circular sheets on the rectangular sheet
Subtracting the circles from the rectangular sheet

(c)

Wrapping the sheet around the rim

(d)

Thickening the wrapped sheet

Figure 3.21 Modeling process of the perforated SBF antenna.
Figure 3.22. Side view of the perforated SBF antenna.

Figure 3.23. Top view of the perforated SBF antenna.
Table 3.5 Optimized design parameters for the perforated SBF antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_m$</td>
<td>Diameter of the main reflector</td>
<td>119.3</td>
</tr>
<tr>
<td>$D_s$</td>
<td>Diameter of the sub-reflector</td>
<td>38.181</td>
</tr>
<tr>
<td>$H_r$</td>
<td>Height of the rim</td>
<td>32.727</td>
</tr>
<tr>
<td>$H_s$</td>
<td>Height of the sub-reflector</td>
<td>38.481</td>
</tr>
<tr>
<td>$R_{choke}$</td>
<td>Distance between the rim and outer diameter of the choke</td>
<td>5.455</td>
</tr>
<tr>
<td>$d_{choke}$</td>
<td>Depth of the choke</td>
<td>16.064</td>
</tr>
<tr>
<td>$W_{choke}$</td>
<td>Width of the choke</td>
<td>16.064</td>
</tr>
<tr>
<td>$W_{iris}$</td>
<td>Width of the iris</td>
<td>4.5</td>
</tr>
<tr>
<td>$a$</td>
<td>Length of the waveguide feed</td>
<td>40.387</td>
</tr>
<tr>
<td>$b$</td>
<td>Width of the waveguide feed</td>
<td>20.193</td>
</tr>
</tbody>
</table>

3.3.2 Performance Analysis

The simulations in this section were conducted to examine the impact of varying the perforation radii from 0 – 5 mm on the antenna’s performance. This includes its gain, impedance bandwidth,
and cross-polarization ratio performance. Figure 3.25 shows the plot of the impedance bandwidth and peak gain as a function of the perforation radius at a 5.5 GHz operating frequency. There was a noticeable steady drop in the impedance bandwidth (38.4–34.9%) with increasing perforation radius (PR), but there was no noticeable effect on the peak gain as it remained constant at a value of ~16.3 dBi.

The surface current distribution of the unperforated and perforated SBF antennas (for PR = 2.5 mm and PR = 4.5 mm) is depicted in Figure 3.26. The surface current distribution changed depending on the radius of the antenna’s perforation. Because of its smaller surface area, the perforated antenna with a PR of 4.5 mm exhibited a higher surface current density on the rim and near the waveguide feed than the antenna design with a PR of 2.5 mm. This also had an impact on the observed variations in bandwidth, as impedance changes with changing current distribution.

![Figure 3.25. The variations in the peak gain and impedance bandwidth as a function of the radius of perforation.](image-url)
Figure 3.26. Surface current density for (a) the unperforated SBF antenna, (b) the perforated SBF antenna (PR = 2.5 mm), and (c) the perforated SBF antenna (PR = 4.5 mm).

Figure 3.27 compares the reflection coefficient of the unperforated antenna (PR = 0) to that of the perforated antenna with increasing perforation radius from 2 - 5 mm. There is very close agreement between the plots with a gradual decrease in the -10 dB impedance bandwidth as the PR is increased. With an increase in the radius of perforation from 0 mm to 5 mm, the impedance bandwidth values dropped from 38.4% to 34.9%.

The worst case cross-polarization ratio results for the perforated SBF antenna as a function of frequency shown in Figure 3.28 showed no changes as the PR is increased from 0 - 5mm between 4.2 – 5.4 GHz. However, noticeable changes were seen between 5.4 – 6 GHz. The unperforated antenna (PR = 0 mm) produced the lowest result of −24 dB at 5.6 GHz as the frequency increased from 5.3 to 6 GHz. As the radius of perforation increased, the cross-polarization ratio started to increase, with a minimum value of −20 dB at 5.4 GHz for PR = 5 mm.
Figure 3.27. Simulated reflection coefficient plot for the 3D-printed perforated antennas with perforation radii of 0 mm to 5 mm.

Figure 3.28. Simulated cross-polarization ratio for perforation radii from 0 mm to 5 mm at $\phi = 45^\circ$.

The E-plane and H-plane radiation patterns for the unperforated 3D-printed SBF antenna and the perforated SBF antenna (for the nickel and silver coated antennas) are shown in Figure 3.29. A summary of the properties of the radiation patterns is given in Table 3.6. The half power beamwidth (HPBW) is $24^\circ$ for all the cases. The side lobe level (SLL) of the unperforated antenna is higher than the nickel and silver coated perforated antennas by 2.03 dB and 1.49 dB, respectively for the E-plane radiation patterns. There are no SLL values for the H-planes because there are no side
lobes for them. The null-null beamwidth is generally larger for the H-plane patterns compared to those of the E-plane. The cross-polarization ratios for all the cases are below -30 dB which shows good isolation. The perforation process also reduced the front-back ratio of the radiation patterns compared to the unperforated antenna’s radiation pattern by 3.44 dB and 1.36 dB for the nickel and silver coated antennas respectively.

The worst-case cross-polarization ratio can be obtained from the radiation pattern at $\phi = 45^\circ$ which is shown in Figure 3.30. The worst case cross-polarization ratio of the unperforated antenna is 20.6 dB (16.21-(4.21)) while that of the nickel and silver coated unperforated SBF antennas are 18.51 dB (16.41-(2.10)) and 17.72 (15.38-(2.34)), respectively.
Figure 3.29. Simulated E-plane ($\phi = 0^\circ$) (left side) and H-plane ($\phi = 90^\circ$) (right side) radiation patterns for the 3D-printed SBF antenna at 5.5 GHz: (a) unperforated; (b) perforated (nickel-coated); (c) perforated (silver-coated).

Figure 3.30. Simulation results of radiation pattern of the 3D printed SBF antenna at $\phi = 45^\circ$ and 5.5 GHz: (a) unperforated; (b) perforated (nickel-coated); (c) perforated (silver-coated).
Table 3.6. Properties of the radiation patterns for the unperforated and perforated SBF antennas.

<table>
<thead>
<tr>
<th></th>
<th>Unperforated</th>
<th>Perforated coated</th>
<th>(nickel-coated)</th>
<th>(silver-coated)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HPBW (Half power beamwidth)</strong></td>
<td>12°–(-12°) = 24°</td>
<td>12°–(-12°) = 24°</td>
<td>12°–(-12°) = 24°</td>
<td>12°–(-12°) = 24°</td>
</tr>
<tr>
<td><strong>SLL</strong></td>
<td>16.21 – 4.85 = 11.36 dB</td>
<td>N/A</td>
<td>15.38 – 6.05 = 9.33 dB</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Null-null beamwidth</strong></td>
<td>28° - (-28°) = 56°</td>
<td>34° - (-34°) = 68°</td>
<td>26° - (-26°) = 52°</td>
<td>30° - (-30°) = 60°</td>
</tr>
<tr>
<td><strong>Cross-pol ratio</strong></td>
<td>16.21 – (-34.78) = 50.99 dB</td>
<td>16.21 – (-35.09) = 51.3 dB</td>
<td>15.38 – (-39.22) = 54.6 dB</td>
<td>15.38 – (-44.42) = 59.8 dB</td>
</tr>
</tbody>
</table>

3.3.3 Other Perforated Antenna designs

This section discusses previous perforated SBF antennas that were designed before selecting the antenna with the 3x37 circular array of perforations as the optimum design. By using the 3x37 array design, it was possible to achieve a maximum perforation radius of 5mm. Exceeding this limit would result in overlapping perforations, which is undesirable.

Therefore, several studies were carried out to determine the best design to obtain the maximum volume reduction while maintaining a good performance (especially the gain). The design goals for the different designs include:

1. Reducing the size and increasing the number of circular holes.
2. Increasing the size and reducing the number of circular holes.
A. Perforated SBF antenna with a 4x48 circular array of holes

The design shown in Figure 3.31 consists of 4x48 array of perforations. The perforations are more in number but smaller in size compared to the proposed design. The maximum perforation radius that can be achieved for this design is 3 mm. The gain and reflection coefficient results are given in Figure 3.32 for a perforation radius of 3 mm. A peak gain of 16.38 dBi was obtained at 5.5 GHz while the impedance bandwidth was 34.2% (4 - 5.65 GHz).

![Figure 3.31. Geometry of the SBF antenna with a 4x48 circular array of perforations.](image)

![Figure 3.32 Simulated results for the SBF antenna with a 4x48 circular array of perforations: a) Reflection coefficient; (b) Realized gain.](image)
B. Perforated SBF antenna with a 2x26 circular array of holes

Another design where the holes have larger radius than 5 mm, but fewer numbers of perforation was created and illustrated in Figure 3.33. The maximum radius of perforation that can be obtained with this design is 7 mm. This was done to study how larger perforations affect the antenna performance and if it will produce a higher mass reduction compared to the proposed design. The simulation results for this design with the maximum radius of 7 mm are shown in Figure 3.34. The simulated impedance bandwidth and peak realized gain are 32.6% and 15.75 dBi, respectively.

![Geometry of the SBF antenna with a 2x26 circular array of perforations.](image)

Figure 3.33. Geometry of the SBF antenna with a 2x26 circular array of perforations.

![Simulated results for the SBF antenna with a 2x26 circular array of perforations.](image)

Figure 3.34. Simulated results for the SBF antenna with a 2x26 circular array of perforations: a) Reflection coefficient; (b) Realized gain.
To quantify the effectiveness of each design in reducing the mass of the antenna, the total volume of the perforations was calculated and will be proportional to the reduction in mass. The higher the volume of the perforations, the more mass is reduced. The volume of the SBF antenna can be easily calculated by adding the volumes of the rim and the larger reflector.

Volume of the rim = thickness *[Height of rim * Circumference of the large reflector]

\[ = 2 \times (32.727 \times (2\pi R)) \text{ where } R = \frac{D_m}{2} = 60 \text{ mm, and thickness (t) = 2 mm} \]

\[ = 24,675.6 \text{ mm}^3 \]

Volume of the reflector = \( (\pi R^2) \times t = 22,619.5 \text{ mm}^3 \)

Volume of SBF antenna = 24,675.6 + 22,619.5 = 47,295.1 mm\(^3\)

Volume of r-mm radius of perforation = \((\pi r^2)\)

Total volume of perforations = \((\text{No. of circles} \times \text{Volume of r-mm radius perforation})\)

Total volume of the perforated antenna = Volume of the SBF antenna – Total volume of perforations.

The calculated volumes for the different designs are summarized in Table 3.7. As seen in the table, the proposed design with the 3 rows of perforation produced the highest percentage of volume reduction (36.9%). Even though the gain and bandwidth performance of the 4x48 array design was very good and similar to the proposed design, the percentage of volume reduction is 14% less than that of the proposed design. While the total volume of holes for the 2x26 array design is comparable to that of the proposed design, a gain loss of about 0.66 dB was observed. Based on these findings and comparing the amount of volume reduction and gain values, the proposed design gave the best results.
Table 3.7. Total volume calculation for the circular perforations.

<table>
<thead>
<tr>
<th>Radius (mm)</th>
<th>Volume of one hole (mm³)</th>
<th>3x37 array design</th>
<th>2x26 array design</th>
<th>4x48 array design</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total volume of holes (mm³)</td>
<td>% volume reduction</td>
<td>Total volume of holes (mm³)</td>
</tr>
<tr>
<td>2.0</td>
<td>25.1</td>
<td>2789.4</td>
<td>5.9</td>
<td>1306.76</td>
</tr>
<tr>
<td>2.5</td>
<td>39.3</td>
<td>4359.0</td>
<td>9.21</td>
<td>2042.04</td>
</tr>
<tr>
<td>3.0</td>
<td>56.5</td>
<td>6275.9</td>
<td>13.3</td>
<td>2940</td>
</tr>
<tr>
<td>3.5</td>
<td>77.0</td>
<td>9004.3</td>
<td>19.0</td>
<td>4001.92</td>
</tr>
<tr>
<td>4.0</td>
<td>100.5</td>
<td>11763.2</td>
<td>24.9</td>
<td>5228.08</td>
</tr>
<tr>
<td>4.5</td>
<td>127.2</td>
<td>14887.1</td>
<td>31.5</td>
<td>6616.48</td>
</tr>
<tr>
<td>5.0</td>
<td>157.1</td>
<td><strong>17438.1</strong></td>
<td><strong>36.9</strong></td>
<td>8169.2</td>
</tr>
<tr>
<td>6.0</td>
<td>226.2</td>
<td>N/A</td>
<td>11762.4</td>
<td>24.9</td>
</tr>
<tr>
<td>7.0</td>
<td>307.9</td>
<td>N/A</td>
<td><strong>16010.8</strong></td>
<td><strong>33.9</strong></td>
</tr>
</tbody>
</table>

C. Elliptical shaped perforations

The geometry of the SBF antennas with the elliptical perforations are shown in Figure 3.35 and Figure 3.36. The first design consists of 26 vertical major axis elliptical perforations where the vertical axis is longer than the horizontal axis. The second design consists of 3x11 horizontal major axis elliptical array of perforations where the horizontal axis of each perforation is longer than the vertical axis.

The simulation results for the two designs are shown in Figure 3.37 and Figure 3.38. The 1x26 and the 3x11 elliptical perforation designs had peak gain of 11.73 dBi and 13.73 dBi respectively.
When compared to the proposed design, using this shape of perforation led to a drastic gain loss of 4.68 dB and 2.68 dB for the 1x26 and the 3x11 elliptical perforation designs, respectively.

The dimensions and volume calculations of the two designs are as follows:

**Design 1** (SBF antenna with a 1x26 elliptical array of perforations): \( r_1 = 16 \text{ mm}, r_2 = 6.4 \text{ mm} \) (aspect ratio = 0.4); where \( r_1 \) and \( r_2 \) are the vertical and horizontal radii of the elliptical perforation.

Volume of an elliptical perforation = \( (\pi \times r_1 \times r_2) \times t = 643.4 \text{ mm}^3 \)

Volume of total perforations = Total number of perforations \( \times 643.4 \text{ mm}^3 = 16728.4 \text{ mm}^3 \)

\% Volume reduction = **35.4%**

**Design 2** (SBF antenna with a 3x11 elliptical array of perforations): \( r_1 = 5 \text{ mm}, r_2 = 16.5 \text{ mm} \) (aspect ratio = 3.3)

Volume of an elliptical perforation = \( (\pi \times r_1 \times r_2) \times t = 259.2 \text{ mm}^3 \)

Volume of total perforations = Total number of perforations \( \times 259.2 \text{ mm}^3 = 8553 \text{ mm}^3 \)

\% Volume reduction = **18.1%**

The volume of the first design was calculated to be 16728.4 mm\(^3\), which is almost twice the volume of the second design (8553 mm\(^3\)) and similar to the volume of the proposed design. Despite this, these designs were not selected due to the high gain loss they experienced.

![Figure 3.35](image_url)  
**Figure 3.35.** Geometry of the SBF antenna with a 1x26 elliptical array of perforations.
Figure 3.36. Geometry of the SBF antenna with a 3x11 elliptical array of perforations.

Figure 3.37. Simulated results for the SBF antenna with a 1x26 elliptical array of perforations: a) Reflection coefficient; (b) Realized gain.
From the simulation studies of these designs, it can be concluded that the circular perforations produced better results in terms of the realized gain compared to the elliptical perforations. It was also observed that the antenna starts experiencing gain loss when the perforation size started getting too large. For most of the designs, the reflection coefficient result did not change much with the different designs.

3.3.4 Fabrication and Testing of the Perforated Short Backfire Antenna

The perforated SBF antenna was also fabricated at the University of Manitoba’s ECE machine shop but with a different type of 3D printer. The perforated SBF antenna prototype was printed using the Anycubic Kobra Max 3D printer shown in Figure 3.39. Just like the Airwolf printer, the Anycubic 3D printer also supports a wide range of filaments.

During construction, a 4.5 mm perforation radius was used for the SBF antenna. However, when printed with ABS plastic, deformities and stringing occurred around the perforated sections. As a result, the PLA thermoplastic filament was the preferred material for constructing the perforated antenna. Stringing is a common issue that occurs during the 3D printing process, where thin plastic strings are left on the printed model. This problem is mainly due to the excessive extruder temperature, causing the filament to overheat and ooze out of the nozzle. ABS filament with a
higher melting (200°C) point are particularly prone to this issue and can cause significant problems. Using PLA with a lower melting point of 173°C reduced stringing and improved print quality. The performance of two types of metal paints were compared: silver (Ag) and nickel (Ni) conductive paints. Two prototype perforated SBF antennas were 3D printed to compare the performance of these two paints. The silver conductive paint has better EMI/RFI shielding and a lower resistance ($1.2 \times 10^{-6} \ \Omega \cdot \text{m}$) compared to the nickel conductive paint. Perforated antennas 3D-printed using SBF were manufactured and are shown in Figure 3.40. One prototype was coated in silver and the other in nickel.

The same foam material that was used for the previous design supported the sub-reflector. However, through simulations and experiment, the same thickness of about 30 mm that was used for the unperforated prototype produced a high gain loss ($\sim 1$ dB) for the perforated antenna. This gain loss is as a result of the higher surface current density in the perforated SBF antenna. Consequently, rather than using the 30 mm thick foam that was used for the prior design, a thinner foam with a thickness of 10 mm was employed to support the sub-reflector.

The reflection coefficient measurement (S11) was done first by connecting the antenna’s port to the first VNA port. The measurement process was carried out twice for the two prototypes coated in silver and nickel. Figure 3.41 shows the simulated and measured S11 plots for the nickel and silver coated perforated SBF antennas. The influence from the waveguide can be easily seen in the measured results as it has more disturbances compared to the simulated results, especially at the lower frequency range of 4.1 – 4.3 GHz. SR values of 1 $\Omega/$sq and 0.1 $\Omega/$sq, respectively, were used to generate the simulated S11 values for the nickel and silver prototypes. These values were selected because they gave the same simulation to measurement gain loss ratio as the aluminum prototype, as will be discussed later in this section. There is no significant difference between the measured results for both the silver and nickel coatings, the impedance bandwidths of both cases were measured as 31.5 % (1.52 GHz). The pattern of the measured S11 plots and the impedance bandwidth value are also very close in agreement with the simulated S11 result for the 4.5mm perforation case (35.8 %).
Figure 3.39 The Anycubic Kobra Max 3D printer.

Figure 3.40 Fabricated perforated SBF antenna prototypes: silver-coated (left) and nickel-coated (right).
Figure 3.41 Simulated and measured S11 result for the perforated SBF antenna with different metal coatings.

Figure 3.42 depicts the configuration for the far-field measurement of the perforated SBF antenna in the compact range. The antenna is mounted on the positioning system to be rotated in different directions and different polarizations for the far-field measurement.
The simulated and measured radiation pattern results for the nickel-coated and silver-coated perforated SBF antennas are shown in Figure 3.43. The simulated gain was 15.3 dBi for nickel (SR = 1 Ω/sq) and 16.2 dBi for silver (SR = 0.1 Ω/sq), but the measured peak gains for the nickel and silver coated antennas were 14.2 dBi and 15.2 dBi, respectively. These data clearly show that, in comparison to the nickel paint, employing the silver paint greatly boosted the gain by about 1 dB approximately. As in the previous section, assuming about ~0.6 dB loss was due to the coaxial cable to waveguide insertion loss and the insufficient bonding between the waveguide and the antenna, the remaining ~0.4 dB loss can be attributed to the imperfections introduced by the 3D-printing process.
Figure 3.43. Radiation pattern results for the perforated 3D-printed SBF antenna at (a) $\phi = 0^\circ$, (b) $\phi = 45^\circ$, and (c) $\phi = 90^\circ$. The dashed lines represent $E_\theta$, while the solid lines represent $E_\phi$.

It was important to use silver paint with greater conductivity to reduce losses in the perforated antenna because simulations showed that the perforated rim had a larger surface current than the unperforated prototype. The worst-case cross-polarization ratios at 5.5 GHz were observed to be -17.3 dB and -18.7 dB for the antennas coated in nickel and silver, respectively, for $\phi = 45^\circ$ and $\theta = -45^\circ$. The weight of the perforated antenna was also measured with a weighing scale to be 103 g. This corresponds to approximately 20% of the weight of the aluminum antenna (462.5 g).

Table 3.8 compares the performances of the aluminum, unperforated, and perforated 3D-printed prototypes. The use of 3D-printing technology alone reduced the weight of the antenna by 70%, from 462 g to 139 g. And the perforation approach further reduced it by 80% to 103 g as shown in Figure 3.44. Although there was some loss in gain, the performance of the 3D-printed antenna was satisfactory and met the design specifications. It was also comparable to the original aluminum construction.
Table 3.8. Comparison between the performance of the fabricated aluminum and 3D-printed prototypes.

<table>
<thead>
<tr>
<th></th>
<th>Aluminum SBF antenna</th>
<th>3D-printed SBF antenna</th>
<th>Perforated 3D SBF antenna (Silver coated)</th>
<th>Perforated 3D SBF antenna (Nickel coated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>462.5</td>
<td>139</td>
<td>103</td>
<td>103</td>
</tr>
<tr>
<td>Measured Gain (dBi)</td>
<td>15.7</td>
<td>15.0</td>
<td>15.2</td>
<td>14.2</td>
</tr>
<tr>
<td>Impedance Bandwidth (%)</td>
<td>27.3%</td>
<td>27.7%</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>Cross-polarization ratio (dB)</td>
<td>20.9</td>
<td>19.9</td>
<td>18.3</td>
<td>17.3</td>
</tr>
</tbody>
</table>

3.4 Chapter Summary

In this chapter, two techniques for reducing the mass of the SBF antenna were investigated. The first antenna was fabricated using additive manufacturing techniques. Therefore, simulation
studies were carried out to determine the effects of this process on the SBF antenna, especially the surface roughness that is introduced. It was found that the principle causes of gain reduction were the surface roughness and the increased surface impedance, while the impedance bandwidth and cross-polarization performance experience minimal changes. The antenna was fabricated using the FDM 3D-printing technique and measured. The mass of the 3D-printed antenna was weighed to be approximately 70% less than the aluminum prototype with a gain loss of 0.7 dB when compared to the aluminum prototype.

The perforation technique was applied to the SBF antenna in the second section to further reduce the overall antenna mass. Several parametric studies were done to determine the right size, shape, and arrangement of the perforations on the antenna to obtain the best performance in terms of mass reduction and gain performance. The 3x37 circular array of perforations of radius 4.5 mm was found to be the optimal design. The chosen design was also 3D-printed and tested. The weight of the perforated 3D-printed antenna was 80% less than the weight of the aluminum prototype. Using the nickel conductive paint for this design resulted in a higher gain loss (1.5 dB) because of its lower conductivity compared to using silver paint because of the higher surface current density of the perforated antenna. The measured gain of this design with the silver paint was only 0.5 dB less than that of the unperforated aluminum prototype.

Although these antennas could have been fabricated using traditional methods, the AM process has the advantage of reducing both the cost and time of production. In addition to this, fabricating the perforated SBF antenna with traditional subtractive manufacturing techniques would have been a more difficult process compared to the AM technique as it was a more complex design.

The antennas presented in this chapter were compared with other similar low-mass antenna designs in the literature to emphasize their advantages in Table 3.9. The lightweight perforated antenna presented in [11] used metallic filaments (which is heavier than plastic filaments) in the metal-direct printing 3D printing process. Thus, even with the application of the perforation technique, the mass reduction was only around 63.8%, as opposed to the 80% that was obtained in this study through the use of plastic filaments. Applying only the perforation technique as described in [12] and [100] resulted in only ~50% reduction in mass. The mass reduction percentages of the thermoplastic filament antennas published in [24] and [80], and the antennas described in this study were comparable. However, the gain loss of the K-band Horn antenna was about 1 dB and
employed a very expensive additive manufacturing process [80], compared to the perforated SBF antenna that only experienced a gain loss of 0.5 dB with a much lower fabrication cost.

Table 3.9. Performance comparison of the proposed antennas with other antenna designs

<table>
<thead>
<tr>
<th>Description</th>
<th>Mass reduction technique</th>
<th>Frequency Range (GHz)</th>
<th>Impedance BW (%)</th>
<th>Peak gain (dBi)</th>
<th>Mass reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work 3D printed SBF antenna</td>
<td>3D printing and nickel plating</td>
<td>4-7</td>
<td>27.7</td>
<td>15.0</td>
<td>70</td>
</tr>
<tr>
<td>This work Perforated 3D printed SBF antenna</td>
<td>3D printing and perforation technique</td>
<td>4-7</td>
<td>31.5</td>
<td>15.2</td>
<td>80</td>
</tr>
<tr>
<td>Lightweight Perforated Horn Antenna [11]</td>
<td>3D printing (metal-direct-printing technology) and perforation technique</td>
<td>8-12</td>
<td>40</td>
<td>11.2</td>
<td>63.8</td>
</tr>
<tr>
<td>Lightweight dual cylindrical reflector antenna [12]</td>
<td>Perforation technique</td>
<td>9-14</td>
<td>17</td>
<td>3</td>
<td>50</td>
</tr>
<tr>
<td>Compact Low Weight High Gain Broadband Cassegrain Antenna [101]</td>
<td>Grid wires and composite technology</td>
<td>8-10</td>
<td>50</td>
<td>34.5</td>
<td>50</td>
</tr>
<tr>
<td>Horn Antenna Covered with a 3D-Printed Meta-surface [24]</td>
<td>3D printing and copper plating on ABS printed horn</td>
<td>10-18</td>
<td>66.67</td>
<td>25</td>
<td>80</td>
</tr>
<tr>
<td>K-band Horn Antenna with Charge-Programmed Deposition 3D Printing [80]</td>
<td>Charge-Programmed Deposition 3D Printing</td>
<td>17.5-20.5</td>
<td>15.8</td>
<td>14.31</td>
<td>80</td>
</tr>
</tbody>
</table>
4. Gain and Bandwidth Enhancement of the Short Backfire Antenna

In this chapter, techniques for improving the gain and bandwidth of the short backfire antenna are presented. Several techniques have been used to improve the gain of similar antenna types such as the horn and cavity antennas, to keep the design relatively simple and compact, the aperture flaring technique was employed. For this technique, the aperture opening of the SBF antenna (upper diameter of the antenna’s rim) is widened to create a horn-like design thereby improving the impedance matching at the edge of the aperture. The simulated antenna gain increased from 14.8 dBi to 17.2 dBi and the bandwidth increased from 26.4% to 55% using this technique. While flaring the SBF antenna’s rim increases the gain, over flaring can lead to gain loss due to an increase in the phase error. Therefore, parametric studies were performed to determine the effects of both the flaring angle and the rim height on the gain, bandwidth, and cross polarization ratio of the SBF antenna.

As a way to further improve the impedance matching and impedance bandwidth, I added an inductive iris at the opening of the waveguide feed. The impedance bandwidth of the antenna improved from 54.4% to 66.9% while maintaining the gain and cross polarization performance of the antenna. To optimize the dimensions of the iris, a parametric study on the effects of the width of the iris on the antenna performance was done. A third feature that was added to this design is the 3D-printed plastic superstrate lid as a way to support the sub-reflector at the required height. This design ensures the rigidity of the antenna compared to previous designs that used foam materials.

4.1 Flared Short Backfire Antenna Design Concept

The geometries of the flared SBF antenna are shown in Figure 4.1 - Figure 4.3. This design is similar to the waveguide-fed unperforated SBF antenna design discussed in chapter 3 and consists of the same parts. The only difference is in the design of the rim. Unlike the previous antenna that had a cylindrical shaped rim, the opening of the rim in this design was flared creating a funnel shaped rim. The optimized dimensions for the flared SBF antenna are given in Table 4.1.
Figure 4.1. Geometry of the flared SBF antenna.

Figure 4.2. Side view of the flared SBF antenna.
Figure 4.3. Top view of the flared SBF antenna.

Table 4.1. Simulated parameters for the flared SBF antenna.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_m )</td>
<td>Diameter of the main reflector</td>
<td>110 mm</td>
</tr>
<tr>
<td>( D_u )</td>
<td>Upper diameter of the rim</td>
<td>( D_m + 2 \cdot \text{Hr} \cdot \tan \theta )</td>
</tr>
<tr>
<td>( D_s )</td>
<td>Diameter of the sub-reflector</td>
<td>38.181</td>
</tr>
<tr>
<td>( \text{Hr} )</td>
<td>Height of the rim</td>
<td>32.727</td>
</tr>
<tr>
<td>( \text{Hs} )</td>
<td>Height of the sub-reflector</td>
<td>38.481</td>
</tr>
<tr>
<td>( R_{\text{choke}} )</td>
<td>Distance between the rim and outer diameter of the choke</td>
<td>5.455</td>
</tr>
<tr>
<td>( d_{\text{choke}} )</td>
<td>Depth of the choke</td>
<td>16.064</td>
</tr>
<tr>
<td>( W_{\text{choke}} )</td>
<td>Width of the choke</td>
<td>16.064</td>
</tr>
<tr>
<td>( a )</td>
<td>Length of the waveguide</td>
<td>40.387</td>
</tr>
<tr>
<td>( b )</td>
<td>Width of the waveguide</td>
<td>20.193</td>
</tr>
</tbody>
</table>
4.2 Performance Analysis

In this study, the upper diameter of the antenna’s rim is flared in a manner similar to the horn antenna’s design in order to boost the gain. The flare angle has a big impact on the gain, just like in the case of the horn antenna. The gain rises together with the flare angle until it reaches the optimal flare angle, after which the antenna’s gain begins to fall. The impedance bandwidth of the SBF antenna design is significantly improved when the rim is flared.

4.2.1 Effects of the flaring angle

The flaring angle ($\theta_f$) was increased in this parametric from 0$^\circ$ to 40$^\circ$ in steps of 5$^\circ$ while maintaining the same values for all other variables. The purpose of this investigation was to examine the impact of increasing the flaring angle on the performance of the antenna. In terms of the flaring angle, the upper diameter of the rim ($D_U$) can be expressed as $D_U = D_m + 2H_r \tan \theta_f$, where $H_r$ is the rim’s height and $D_m$ is the diameter of the lower part of the rim, which is also the diameter of the main reflector. The simulations in this section all used $H_r = 0.6\lambda$, which is the optimized rim height from the study of the unflared SBF antenna. The result of the unflared antenna ($\theta_f = 0^\circ$) was compared to the results of the flared SBF antenna at various flaring angles.

Figure 4.4a-b shows the simulated reflection coefficient (S11) plots of the flared SBF antenna with varying flaring angle. From these results, it is observed that increasing the flaring angle from 0$^\circ$ to 10$^\circ$ only caused a small change in the impedance bandwidth as it only increased from 26.4% (4.61 – 6.01 GHz) to 28.1% (5.85-4.41 GHz) respectively. The S11 result for $\theta_f = 10^\circ$ shifted to the left and the impedance matching can be seen to improve as the plot is lower than that of $\theta_f = 0^\circ$. As the flaring angle is increased further, a large improvement can be seen in both the impedance matching and the impedance bandwidth with the largest impedance bandwidth of 55% (4.36-7.67 GHz) observed at $\theta_f = 15^\circ$ (Figure 4.5), this corresponds to more than twice the impedance bandwidth obtained for the unflared SBF antenna. This bandwidth increase is a result of an improved impedance matching caused by the flaring of the antenna (Figure 4.4a). The plots can be seen shifting downwards from 0$^\circ$ - 20$^\circ$, then it starts to move upwards after 20$^\circ$. 
Figure 4.4. Reflection coefficient result of the flared SBF antenna with varying flaring angles from: a) $0^\circ$ - $10^\circ$; (b) $20^\circ$ - $40^\circ$. 
Figure 4.6 shows the results of the simulated gain for the flared SBF antenna. The peak realized gain plot for flaring angles 0° to 40° as a function of frequency is displayed in Figure 4.6a, while Figure 4.6b provides the peak realized gain trend as a function of the flaring angle at a frequency of 5.5 GHz. At a center frequency of 5.5 GHz, the peak realized gain increased by 2.4 dB from 14.8 dBi to 17.2 dBi as the flaring angle was raised from 0° to 20°. As was mentioned in earlier sections, the improved impedance matching at the antenna’s aperture edge is the outcome of less back reflection of waves, which also leads to an improvement in gain. It is evident from the graphs that the gain is not enhanced by further increasing the flaring angle from 20° to 40°. When the flaring angle was raised from 20° to 25°, there was a small decline in gain from 17.2 dBi to 17.1 dBi. However, by increasing it from 25° to 40°, the realized gain fell sharply from 17.1 dBi to 14.3 dBi. The primary cause of this is an increase in phase error brought on by too much flaring. By applying the 3dB gain definition, the 20° flaring angle yielded the broadest gain bandwidth of 1.1 GHz or 21% (4.7 to 5.8 GHz). Based on these findings, it can be concluded that 20° is the optimum flaring angle for this design in order to maximize gain.
Figure 4.6. Flared SBF antenna’s peak realized gain as a function of: a) frequency; (b) flaring angle.

The worst-case cross-polarization ratio at $\theta = 45^\circ$ is displayed in Figure 4.7. The findings indicate that the cross-polarization ratio went higher as the flaring angle increased from $0^\circ$ to $40^\circ$. The unflared antenna has a minimum cross-polarization ratio of -24 dB at 5.6 GHz, but the flared antenna has minimum cross-polarization ratios of -23.27 dB (5.8 GHz), -21.32 dB (5.6 GHz), -19.43 dB (5.4 GHz), and -14.84 dB (5.4 GHz) at $\theta_f = 10^\circ$, 20$^\circ$, 30$^\circ$, and 40$^\circ$, respectively. While this study indicates a general rise in the cross-polarization ratio, it was discovered that the increase...
is not as large at lower flaring angles, like 10° and 20°, as it is at higher flaring angles, like 30° and 40°.

Figure 4.7. Cross-polarization result of the flared SBF antenna with varying flaring angles from 0° - 40°.

Table 4.2. A summary of the effects of the flaring angle on the flared SBF antenna.

<table>
<thead>
<tr>
<th>Hr</th>
<th>θf (°)</th>
<th>DU (mm)</th>
<th>Realized gain @ 5.5 GHz (dBi)</th>
<th>Imp. BW (%)</th>
<th>Min. cross-polar. Ratio (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6 λ</td>
<td>0</td>
<td>110</td>
<td>14.8</td>
<td>26.4</td>
<td>-24</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>121.5</td>
<td>16.3</td>
<td>28.1</td>
<td>-23.27</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>133.8</td>
<td>17.2</td>
<td>54.4</td>
<td>-21.32</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>147.8</td>
<td>16.0</td>
<td>43.1</td>
<td>-19.43</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>165</td>
<td>14.3</td>
<td>42.4</td>
<td>-14.84</td>
</tr>
</tbody>
</table>

Table 4.2 provides an overview of the flared antenna’s performance. The impedance bandwidth increased together with the flaring angle, peaking at θf = 15° before progressively declining. As the flaring angle increased until θf = 20°, an improvement in gain was also observed. On the other hand, the cross-polarization decreased with increasing flaring angle. Although θf = 15° gave the largest bandwidth, the gain obtained at this angle was about 1 dB less than the highest gain, while
the bandwidth at \( \theta_f = 20^\circ \) is only 0.6\% lower than the largest bandwidth. Based on the simulation results and observations, the optimum flaring angle for the design is 20\°.

### 4.2.2 Effects of the rim height

The second parametric study focuses on how the rim height affects the flared SBF antenna’s gain, impedance bandwidth, and cross polarization ratio. \( \theta_f = 20^\circ \) was chosen as the flaring angle for this section as it offered the highest gain and closest to the widest bandwidth in the preceding section. Although every other variable is kept constant, the upper diameter of the rim (\( D_U \)) will vary due to variations in the height of the rim.

The rim height was increased in steps of 0.1\( \lambda \), from 0.4\( \lambda \) to 0.8\( \lambda \), in order to examine its impact on the antenna’s performance. Figure 4.8 displays the simulated realized gain results for various rim heights. The maximum realized gain at 5.6 GHz rose from 15.41 dBi to 17.22 dBi (an increase of 1.81 dB) when the rim height is increased from 0.4\( \lambda \) to 0.6\( \lambda \); at 5.5 GHz, the gain also improved from 15.27 dBi to 17.02 dBi (a 1.75 increase). When the rim height is changed from 0.6\( \lambda \) to 0.8\( \lambda \), there was no discernible difference in the realized gain. Figure 4.9 shows the cross-polarization ratio results. As the rim height is increased from 0.4\( \lambda \) to 0.8\( \lambda \), the cross-polarization ratio does not change much, however, the lowest cross-polarization ratio of 21.33 dB was obtained at 0.6\( \lambda \).

The antenna’s impedance bandwidth increased from 26.4\% (4.43 - 5.78 GHz) to 55\% (4.35 - 7.60 GHz) when the rim’s height increased from 0.4\( \lambda \) to 0.6\( \lambda \) as illustrated in Figure 4.10. However, as the height was further increased to 0.8\( \lambda \), the percentage of bandwidth plummeted to 29.1\% (4.38-5.87 GHz). This indicates that the height of the rim also impacts that impedance matching.

The summary of the investigation on the effects of the rim height on the flared SBF antenna is provided in Table 4.3. From the table, it can be concluded that the best results in terms of the gain, bandwidth, and cross-polarization ratio were obtained at a rim height of 0.6\( \lambda \), therefore this dimension will be used for the final design.
Figure 4.8. Realized gain result of the flared SBF antenna with varying rim height from $0.4\lambda$ - $0.6\lambda$.

Figure 4.9. Cross-polarization ratio result of the flared SBF antenna with varying rim height from $0.4\lambda$ - $0.6\lambda$.

Figure 4.10. Reflection coefficient result of the flared SBF antenna with varying rim height from $0.4\lambda$ - $0.6\lambda$. 
Table 4.3: A summary of the effects of the rim height on the flared SBF antenna.

<table>
<thead>
<tr>
<th>θf (°)</th>
<th>Hr (λ)</th>
<th>ℓ_U (mm)</th>
<th>Peak gain (dBi)</th>
<th>Gain @ 5.5 GHz (dBi)</th>
<th>Imp. BW (%)</th>
<th>Min. Pol. Ratio (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20°</td>
<td>0.4</td>
<td>125.9</td>
<td>15.41</td>
<td>15.27</td>
<td>26.4</td>
<td>19.73</td>
</tr>
<tr>
<td>0.5</td>
<td></td>
<td>129.9</td>
<td>16.58</td>
<td>16.34</td>
<td>50.6</td>
<td>20.4</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td>133.8</td>
<td>17.22</td>
<td>17.02</td>
<td>55.0</td>
<td>21.32</td>
</tr>
<tr>
<td>0.7</td>
<td></td>
<td>137.8</td>
<td>17.18</td>
<td>17.04</td>
<td>33.0</td>
<td>20.35</td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td>141.8</td>
<td>17.18</td>
<td>17.15</td>
<td>29.1</td>
<td>16.9</td>
</tr>
</tbody>
</table>

4.2.3 Flared SBF with iris design

The length of the waveguide’s aperture (a = 40.387 mm) was shortened on both sides by adding thin metal strips, as seen in Figure 4.11, to further enhance the flared SBF antenna’s reflection coefficient (S11) in this section. Typically, these metal strips are referred to as waveguide iris. Depending on whether it is in the magnetic or electric field’s transverse plane, the waveguide iris can represent an inductance or shunt capacitance. Due to the iris's placement in the magnetic field in this design, an inductive element was created that can match the waveguide’s characteristic impedance to the impedance of the SBF antenna. The impedance bandwidth increases when there is an improvement in impedance matching, which also lowers the S11 result.

In order to determine how the iris affected the flared SBF antenna’s gain, reflection coefficient (impedance bandwidth), and cross polarization ratio, a parametric study was conducted in this section. The iris’s width is adjusted from 1 mm to 5 mm in steps of 2 mm to find the ideal value for optimal performance. The iris’s length is the same as the width of the waveguide feed (b = 20.193 mm). The obtained results are compared with the design that has no iris (0 mm iris width).
Figure 4.11. Geometry of the flared SBF antenna with inductive iris.

Figure 4.12 - Figure 4.15 show the influence of the inductive iris on the peak realized gain, impedance bandwidth, and reflection coefficient (S11) of the flared SBF antenna. Plots of the reflection coefficients at a 20° flaring angle for iris widths ranging from 0 to 5 mm are given in Figure 4.12. The frequency bandwidth for S11 < -10 dB increased from 3.3 GHz or 55% (4.3 – 7.6 GHz) to 3.85 GHz or 66.7% (3.85 – 7.7 GHz) when the width of the iris is changed from 0 to 3 mm. With an increase in the iris width from 3 to 5 mm, the bandwidth decreases to 62.2% (4.1 – 7.8). Due to the wide bandwidth of the antenna, the 3 mm iris width offers the best impedance matching between the SBF antenna and the wave-guide feed.

Figure 4.12. Reflection coefficient result of the flared SBF antenna with varying iris width from 0 - 5 mm.
The smith chart of the flared SBF antenna comparing the impedances of the antenna with no iris and with a 3mm iris is shown in Figure 4.13. This chart plots the normalized complex (real and the imaginary) impedance from 3.8 GHz to 8 GHz. The closer the plots are to the R = 1.0 value, the more matched the input impedance. The values of the no iris case are between 0.5 to 2.83 on the real scale while the values of the 3 mm iris case are between 0.55 to 1.53. The impedance of the 3 mm iris case is closer to R = 1, therefore it is more matched than the antenna without the iris.

Figure 4.13. A Smith chart plot of the flared SBF antenna no iris and 3mm iris cases

The effects of the iris on the realized gain and cross-polarization ratio of the flared SBF antenna are shown in Figure 4.14 and Figure 4.15. As observed in the figures, adding an iris does not affect the flared SBF antenna’s gain or cross-polarization ratio. For all the simulated iris widths, the maximum achieved gain and lowest cross-polarization ratio were ~17 dBi and -21 dB at 5.6 GHz, respectively. Since the iris’s main function is to enhance impedance matching, this behavior was anticipated.
Figure 4.14. Peak realized gain result of the flared SBF antenna with varying iris width from 0 - 5 mm.

Figure 4.15. Cross-polarization result of the flared SBF antenna with varying iris width from 0 - 5 mm.

4.2.4 Flared SBF antenna with a superstrate lid

Foam materials were used in the previous waveguide-fed SBF antenna designs to support the sub-reflector at the right distance from the main reflector. While prototyping has been made easier by the foam material, it is not sturdy enough to hold the sub-reflector in place and might easily collapse into the main reflector. In order to address this problem a thin, plastic-based superstrate was designed that is strong enough to hold the sub-reflector in place while having little to no impact on the antenna’s functionality. In addition, the superstrate can be easily 3D printed.

The geometry of the flared SBF antenna with the superstrate lid is shown in Figure 4.16. The lid is made up of two attached parts: a thin disk with a hole in the center, and a rim that encircles the
hole that holds the sub-reflector. From initial simulations, it was found out that covering the sub-reflector completely with the lid caused a higher gain loss compared to leaving the hole in the center which is almost the same diameter as that of the sub-reflector, to expose the reflective surface. It is also important to keep the thickness of the lid as small as possible as dielectric materials can cause gain loss due to the reduced transmission of EM waves. The rim is added around to hole to make up for the remaining distance between the disk and the sub-reflector. The thickness of the disk, the lid’s rim, and the sub-reflector are indicated by the measurements $t_{S1}$, $t_{S2}$, and $t_{Sub}$.

Two different plastic materials with differing dielectric constants were used for the simulation in order to investigate how the lid affected the antenna’s performance. The polylactic (PLA) plastic has a dielectric constant of 2.1, while the acrylonitrile butadiene styrene (ABS) plastic has a dielectric constant of 3.1. These values can change experimentally due to the fabrication process. To achieve optimal design performance, the thickness of the lid’s disk was also examined and varied from 1 mm to 4 mm.

![Figure 4.16. The flared SBF antenna with the superstrate lid.](image-url)
The simulated S11 results for the flared antenna with the lid are shown in Figure 4.18 and Figure 4.19. It is evident from both graphs that the antenna with the lid increased the S11 result in comparison to the antenna without a lid. The PLA lid, which has a lower dielectric constant, has a less noticeable influence on the antenna than the ABS lid in terms of the reflection coefficient. The antenna with the PLA lid’s S11 result is higher between 4.3 and 5.6 GHz, but it stays below -10 dB, meaning that the bandwidth remains relatively constant. As the PLA lid thickness increased from 1mm to 4 mm, the simulated impedance bandwidth ranged from 62.2% to 67.8%.

The S11 result starts to go above -10 dB at lower frequencies when the ABS lid gets thicker than 1 mm, which significantly reduces the impedance bandwidth. The antenna with no lid had a bandwidth of 66.7%, but the antennas with ABS lids of 1 mm, 2 mm, 3 mm, and 4 mm thickness had impedance bandwidths of 66.4%, 46.4%, 43.2%, and 45.7%, respectively.
Figure 4.18. The reflection coefficient of the flared SBF antenna with the PLA lid.

Figure 4.19. The reflection coefficient of the flared SBF antenna with the ABS lid.

Figure 4.20 and Figure 4.21 compare the peak simulated gain of the SBF antenna with the PLA and ABS lids to the antenna without a lid. A general trend observed is that as the lid thickness increases, the gain decreases. However, compared to ABS, which has a higher dielectric constant, the PLA lid experiences lower gain loss. The greatest gain loss is seen at 5.6 GHz and with a 4 mm lid thickness. For example, the PLA and ABS lids with a lid thickness of 4 mm have peak gains of 15.7 dBi and 10.8 dBi, respectively, at 5.6 GHz, but the lidless antenna has a peak gain of 17.02 dBi. The smallest gain loss was observed with the thinnest lid (1 mm). The antenna with PLA and
ABS lids at 5.6 GHz with a 1 mm lid thickness showed peak gains of 17.01 dBi and 16.8 dBi, respectively.

**Figure 4.20.** The peak realized gain of the flared SBF antenna with the PLA lid.

**Figure 4.21.** The peak realized gain of the flared SBF antenna with the ABS lid.

Figure 4.22 and Figure 4.23 provide the worst-case cross-polarization ratio results for the flared antenna with the lids. Between 4.4 and 5.4 GHz, there is no discernible difference between the PLA lid results with the different lid thickness and the no lid case. The minimum cross-polarization
ratio reduced from 21 dB to 17 dB between 5.4 and 5.8 GHz as the lid thickness is increased from 1 mm to 4 mm. The same trend is also observed for the ABS lid where the values are the same between 4.4 and 5.4 GHz. However, between 5.4 and 5.8 GHz, the decrease in the cross-polarization ratio is greater compared to the PLA lid design. This ratio was 13 dB for the 4 mm ABS lid thickness at 5.6 GHz.

![Graph showing cross-polarization ratio](image)

**Figure 4.22.** The cross-polarization ratio of the flared SBF antenna with the PLA lid.

![Graph showing cross-polarization ratio](image)

**Figure 4.23.** The cross-polarization ratio of the flared SBF antenna with the ABS lid.

When selecting a material for the superstrate lid, it’s crucial to choose a material with a lower dielectric constant and to make it as thin as possible to obtain excellent results based on the results of this study.
4.2.5 Effect of the Additive Manufacturing Process

All of the simulation studies in this chapter were done by modelling the flared SBF antenna using a perfect electric conductor (PEC). However, since the antenna will be fabricated using a 3D printer, it is important to simulate the effect of the increased resistivity this process introduces. To do this, a surface impedance boundary is applied to the flared SBF antenna as shown in Figure 4.24. Since the silver conductive paint is used for metallization, the impedance of this boundary was set to 0.1 Ω/sq just like in the perforated SBF antenna case.

The realized gain, reflection coefficient, and the cross-polarization performances were analyzed. The reflection coefficient result is given in results are provided in Figure 4.25. The simulated impedance bandwidth did not change much as it only increased by 1.6 % (62.2% to 63.8%). The radiation patterns of the 3D-printed flared SBF antenna at 5.5 GHz are shown in Figure 4.26. The peak realized gain obtained from the radiation patterns decreased from 17 dBi to 16.78 dBi (0.22 dB gain loss) while the cross-polarization ratio reduced slightly from 21 to 19.8 dB.

![Figure 4.24. The impedance boundary for the flared SBF antenna.](image)
Figure 4.25. Reflection coefficient of the 3D-printed flared SBF antenna.

Figure 4.26. Radiation patterns for the 3D-printed flared SBF antenna at 5.5 GHz: (a) $\phi = 0^\circ$; (b) $\phi = 45^\circ$; (b) $\phi = 90^\circ$. 

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4.3 Fabrication and Testing

The fabrication of this antenna design was also done using the Anycubic Kobra Max 3D printer at the University of Manitoba’s ECE machine shop just like the perforated antenna. The PLA filament was used as it worked better for this design compared to ABS in terms of the quality of the 3D-printed prototype. Further processing to smoothen the surface of the antenna was carried out for this design. To fabricate the flared SBF antenna, ABS plastic was used in the first attempt, as it allowed for the application of the acetone vapor polishing process. While this is a very slow process without the use of any form of heat, the use of heat can make the process uncontrollable and can damage the design. To achieve the best result, the antenna was suspended above the liquid acetone in an enclosed container at room temperature. The antenna had to be left in the container for a long time (almost 24 hours) due to the very slow process. After removing the antenna, parts closest to the antenna were observed to be glossy, and the acetone had penetrated the plastic making it soft to touch. The antenna was then left to dry properly before checking for the final results.

This process did not work for the antenna because of the following reasons:

1. The polishing process was uneven and parts that were closest to the acetone were more polished and absorbed more acetone than the parts that were farther away.
2. After drying the antenna, the antenna shrunk in size which completely changed the dimensions and would have affected the antenna’s performance.

The second polishing process that was attempted involved coating the antenna with the XTC-3D coating. This product consists of two parts: a resin and a hardener that was mixed together. The XTC-3D mixture works by filling in the ridges created by the 3D printing process with the resin mixture when it is applied on the rough 3D-printed object. A thin layer of coat on the inside surface of the antenna was sufficient to create a smooth surface after the liquid dried up and hardened. There was no need for sanding or further processing after this step. This process worked better than the vapor polishing since it did not cause any damage to the antenna.

The entire surface of the antenna was coated with silver conductive spray after the polishing process was completed. The top and bottom views of the coated fabricated antenna are shown in Figure 4.27 and Figure 4.28.
The lid of the antenna was fabricated using PLA since it gave better simulation results compared to ABS. The disk of the fabricated lid was measured to be about 1.5 mm thick. To attach the lid to the SBF antenna, tiny strips of double-sided tape were first attached to the edges of the antenna’s aperture, the lid then adhered to the tapes when it was placed on the antenna’s aperture. The antenna
was assembled with the waveguide feed and measured using the Keysight VNA. The measurement setup is shown in Figure 4.29.

![Image](image.jpg)

Figure 4.29. The fully assembled flared SBF antenna with the PLA lid connected to the VNA.

The measured S11 result is compared to the simulated S11 result for the flared SBF antenna with the 1 mm thick PLA lid in Figure 4.30. The patterns of both plots are in very close agreement. The measured impedance bandwidth of the fabricated antenna was a little lower compared to the simulated result. The measured bandwidth was from 4.5 - 7.8 GHz (53.7%) while the simulated bandwidth was calculated as 62.2% (4.1 – 7.8 GHz). The bandwidth of the flared SBF antenna is almost twice the bandwidth of the unflared SBF antennas.
The far-field radiation pattern measurement was first performed on the flared antenna with the PLA lid. The radiation pattern results at 5.5 GHz are shown in Figure 4.31. The peak gain of the flared antenna with the PLA lid was measured to be 15.42 dBi. A gain loss of 1.36 dB was experienced by the fabricated prototype when compared to the simulated gain results of the 3D printed flared SBF antenna with PLA lid (16.78 dBi). The measured and simulated HPBW were 10.54 – (-10.54) = 21.08° and 11 – (-11) = 22° respectively, while the measured and simulated SLL values are 10.49 dB (15.42 - 4.93) and 9.55 dB (16.78-7.23), respectively. The measured worst case cross-polarization result at $\phi = 45^\circ$ was 20.77 dB (15.34 - (-5.43)), while the simulated cross-polarization ratio was 20.15 dB (16.78 - (-3.37)). Although the other radiation properties of the fabricated antenna are in close agreement with the simulated results, the gain loss for this design was higher than expected.
Figure 4.31. Radiation pattern results for the flared 3D-printed SBF antenna with the PLA lid at (a) \( \varphi = 0^\circ \), (b) \( \varphi = 45^\circ \), and (c) \( \varphi = 90^\circ \). The dashed lines represent the simulated result, while the solid lines represent the measured results.

To investigate if the gain loss experienced by the antenna was caused by the PLA lid, a piece of foam with a known dielectric constant of 1.05 was fabricated to replace the PLA lid, the flared SBF antenna with the foam material is shown in Figure 4.32. The thickness of the foam lid is the distance between the height of the sub-reflector and the height of the rim (\( H_s - H_r = 38.181 - 32.727 = 5.454 \) mm). Additional simulations were done with the foam material so as to compare with the measured results.
The measured and simulated far-field radiation patterns for the flared SBF antenna with the foam lid are compared in Figure 4.33. The figures show the co and cross polarization results of the antenna at 5.5 GHz. The maximum realized gain of the fabricated flared SBF was measured to be 15.7 dBi. Compared to the simulated (flared SBF antenna with the foam lid) peak gain result, which was 16.74 dB, a gain loss of about 1 dB was experienced. The measured and simulated HPBW were 10.5 - (-10.5) = 21° and 11 - (-11) = 22° respectively. The SLL values for the measured and simulated results were 16.74 - 7.23 = 9.51 dB and 15.7 – 5.62 = 10.08 dB, respectively. The close simulation and measurement values of the HPBW and SLL show good agreement between the simulated and fabricated antenna. The gain loss experienced by the antenna with the foam lid was lower than that of the PLA lid. A 0.6 dB gain loss occurs from the measurement connections, while the remaining 0.4 dB gain loss is primarily due to the 3D printing process discussed in the previous chapter. This value is expected to be reduced with an AM technique with a higher resolution and a more advanced metallization process.
The worst case cross-polarization ratios of the simulated and measured results which were obtained at $\phi = 45^\circ$ are also in good agreement with values of $16.74 - (-3.8) = 20.54$ dB and $15.70 - (-4.25) = 19.95$ dB respectively.
Figure 4.33. Radiation pattern results for the flared 3D-printed SBF antenna with the foam lid at (a) $\varphi = 0^\circ$, (b) $\varphi = 45^\circ$, and (c) $\varphi = 90^\circ$. The dashed lines represent the simulated result, while the solid lines represent the measured results.

4.4 Chapter Summary

In this chapter, a combination of techniques was investigated to improve the gain and bandwidth performance of the SBF antenna. The aperture flaring technique was used to improve the gain and bandwidth performance significantly. A flaring angle of $20^\circ$ and a rim height of $0.6\lambda$ gave the optimum performance for this design based on the simulation studies. The inductive iris was also added to the aperture of the waveguide feed to improve the impedance matching which led to an increase in the bandwidth. The third feature that was added to the final design was the PLA lid that acts as a support structure for the sub-reflector.

The flared SBF antenna with the PLA lid was fabricated and the performance was measured to validate the simulation studies. The impedance bandwidth and the cross-polarization ratio was found to be in close agreement with the simulated results. However, a gain loss of $1.36$ dB was obtained. To investigate the cause of this gain loss, the PLA lid was replaced with a foam material with a lower dielectric constant. The gain performance of the antenna with the foam lid was better than with the PLA lid as the gain loss was measured to be $1$ dB. A summary of the performance of
the simulated and fabricated antenna designs is given in Table 4.4. These results showed that the AM process contributes to the gain loss, and it is almost unavoidable. However, the gain loss can be improved using more advanced AM processes.

Table 4.4. A summary of the simulated and measured results of the flared SBF antenna design.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Peak realized gain (dBi)</th>
<th>Impedance bandwidth (%)</th>
<th>Cross-polarization ratio (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated FSBF antenna with the PLA lid (PEC)</td>
<td>17.02</td>
<td>62.2</td>
<td>21.00</td>
</tr>
<tr>
<td>Simulated FSBF antenna with the PLA lid (3D-printed)</td>
<td>16.78</td>
<td>63.8</td>
<td>19.80</td>
</tr>
<tr>
<td>Measured FSBF antenna with the PLA lid</td>
<td>15.42</td>
<td>53.7</td>
<td>20.77</td>
</tr>
<tr>
<td>Simulated FSBF antenna with the foam lid (3D-printed)</td>
<td>16.74</td>
<td>62.5</td>
<td>20.54</td>
</tr>
<tr>
<td>Measured FSBF antenna with the foam lid</td>
<td>15.7</td>
<td>53.7</td>
<td>19.95</td>
</tr>
</tbody>
</table>

A summary of the performance of the unflared and flared SBF antenna is given in Table 4.5. The gain and the bandwidth of the flared antenna can be seen to improve significantly by 0.7 dB and 26 %, respectively, while the cross polarization did not change much when compared to the unflared antenna. As expected, the weight of the flared SBF antenna is higher than that of the unflared antenna, as a result of the increase in the total volume of the antenna and also because ABS which was used to fabricate the unflared antenna is about 25% lighter than PLA used for the flared antenna [102].
Table 4.5 Comparison between the unflared and flared SBF antenna.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Measured Gain (dBi)</th>
<th>Measured Impedance Bandwidth (%)</th>
<th>Measured Cross-polarization ratio (dB)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unflared 3D-printed SBF antenna</td>
<td>15.01</td>
<td>27.7</td>
<td>19.9</td>
<td>139</td>
</tr>
<tr>
<td>Flared 3D-printed SBF antenna</td>
<td>15.7</td>
<td>53.7</td>
<td>20.54</td>
<td>252.5</td>
</tr>
</tbody>
</table>

Table 4.6 Comparison of the flared SBF antenna with other published antenna designs.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Description</th>
<th>Frequency range (GHz)</th>
<th>Impedance bandwidth (%)</th>
<th>Peak gain (dBi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>Flared SBF antenna</td>
<td>4-7</td>
<td>53.7</td>
<td>15.7</td>
</tr>
<tr>
<td>[17]</td>
<td>Waveguide-fed SBF antenna</td>
<td>4-7</td>
<td>27.3</td>
<td>15.7</td>
</tr>
<tr>
<td>[57]</td>
<td>Patch-Fed Short Backfire Antenna</td>
<td>2-2.5</td>
<td>15</td>
<td>15.2</td>
</tr>
<tr>
<td>[103]</td>
<td>Substrate Integrated Waveguide H-plane Horn Antenna</td>
<td>85 - 103</td>
<td>19.6</td>
<td>14.5</td>
</tr>
</tbody>
</table>

To highlight the excellent performance of the flared SBF antenna, it was compared to other similar designs (SBF and horn antennas) that have been published in Table 4.6. This table compares the gain and impedance bandwidth of the antenna designs and also provides the frequency range of operation. There was no information on the weight and the cross-polarization
ratio of these designs, therefore these parameters were not compared. While the gain values are similar to the short backfire antennas in [17] and [57], the impedance bandwidth of the flared antenna is about 2 and 3 times wider, respectively. The flared SBF antenna’s gain also provides a better performance in terms of the gain and bandwidth compared to the antennas published in [103] and [104].
5. Conclusion and Future Work

The goal of this thesis was to achieve low mass short backfire antennas with improved gain and bandwidth performance. To achieve this, several techniques were investigated to decrease the mass and increase the gain and bandwidth of the antenna. This research conducted on the SBF antennas can be categorized into the following area:

1. Fabricating the SBF antenna using additive manufacturing techniques (Chapters 3 & 4)
2. Applying the perforation technique to the SBF antenna (Chapter 3)
3. Gain and bandwidth enhancement using the aperture flaring technique and iris (Chapter 4)

The mass reduction techniques applied to the SBF antennas were investigated in chapter 3. Two candidate antenna designs were presented.

For the first design, the aluminum SBF antenna was implemented using the additive manufacturing technique. This involved fabricating the antenna using lightweight thermoplastic materials such as ABS and PLA, and then coating the surface with conductive metal sprays. The FDM technique, which was the AM technique applied for this design, is known for creating objects with a significant level of surface roughness. Because of this, several studies were conducted to investigate the effect of the surface roughness on the antenna performance. It was found that the gain decreased while the bandwidth increased with increasing surface roughness.

The perforation technique was applied to the second design and was then fabricated using the AM technique. The perforation technique involved creating perforations/holes in the antenna as a way to reduce the mass while maintaining the same performance. Several perforated antenna designs were proposed with different shapes, sizes, and arrangement of perforations. From extensive simulation studies, it was found that the circular shaped holes did not cause a significant degradation in the antenna gain as much as the elliptical perforations. It was also found that perforation radii higher than λ/10 (5.454 mm) started to cause a decline in the gain. From these observations, the antenna with the 3x37 circular array of perforations with a radius of 4.5 mm was chosen as the best design having the highest mass reduction while maintaining excellent performance.

Both antenna designs were fabricated using 3D printers and thermoplastic materials. The fabricated unperforated and perforated 3D printed antennas were measured to 20% and 30% less
than the weight of the aluminum prototype. The peak measured gain values for the unperforated and perforated 3D printed antennas were 15 dB and 15.5 dB respectively. While there is a massive loss of mass, the 3D printed prototypes experienced more gain loss compared to the antenna fabricated with aluminum metal that had a measured gain of 15.7 dB. However, the difference in gain loss is very minimal compared to the mass reduction. This is mostly due to the fabrication process, the conductivity and surface roughness of the 3D printed antennas.

**Future work for the designs in Chapter 3**

To improve the performance of the 3D-printed antennas presented in chapter 3, the following should be investigated:

1. Employing advanced additive manufacturing techniques such as SLA (photopolymerization). Although this technique is more costly than FDM, it has the advantage of having a higher printing resolution which will create more accurate designs with much less surface roughness.
2. Conducting more research on advanced metallization methods such as electroplating and jet metal processing.
3. Measuring and evaluating the precise surface roughness values using LiDAR, profilometer or a laser scanner.
4. Conducting additional optimization studies on the perforated antenna design, including examining combinations of different perforation sizes and the best way to pack the circular holes in a lattice-type structure.

**In chapter 4,** methods for enhancing the gain and bandwidth of the SBF antenna were discussed. Several techniques were combined to make one final design called the flared SBF antenna with an inductive iris.

**Firstly,** the rim of the SBF antenna was flared to improve the impedance matching between the aperture edge and free space. Parametric studies were carried out to determine the effect of the flaring angle and the height of the rim on the antenna’s performance. It was discovered that as the flaring angle increased, the antenna’s gain and bandwidth also increased from 15 to 17.02 dB and from 26.4% to 55%, respectively, until the optimum flaring angle value of 20° is reached. This trend reversed when the flaring angle exceeded the optimum value, leading to a decline in
performance. This decline in performance is caused by an increase in the phase error due to over-flaring. Therefore, it is important to determine this critical point to prevent any degradation in performance. The best rim height was also determined through simulations to be $0.6\lambda$.

Secondly, an inductive iris was added to the opening of the waveguide aperture to improve the impedance matching of the waveguide feed to the SBF antenna. Simulations studies showed that while the bandwidth increased from 55% – 66.7%, the gain and the cross-polarization ratio were not affected and remained at $\sim17$ dB and $\sim21$ dB, respectively. The third addition was the plastic lid that had the purpose of supporting the sub-reflector. From the studies that were conducted, the lid with the lowest dielectric constant and the smallest thickness affected the antenna’s performance the least. Since the antenna was fabricated using a 3D printer, simulations were also done to investigate the effects of the materials used for fabrication on the antenna’s performance.

The antenna was fabricated and measured to validate the simulated results. Two different polishing methods were investigated: acetone vapor polishing and coating the antenna surface with a resin-based liquid. Coating the antenna with resin-based liquid provided a better result compared to the vapor polishing that damaged the antenna. The measured S11 result of the antenna with the PLA lid was very close to the simulated S11 results having values of 53.7 and 62.2 % respectively. The measured gain on the other hand reduced by 1.36 dB compared to the simulated gain. To investigate and improve this gain loss, the PLA lid was replaced by a foam lid. This improved to gain loss from 1.36 dB to 1 dB, since a gain loss of about 0.6 dB was expected due to the imperfect connections with the antenna, the remaining 0.4 dB gain loss can be attributed to the AM process.

**Future work for the designs in Chapter 4**

To improve the performance of the flared SBF antenna presented in chapter 4, the following should be investigated:

1. Investigate more low dielectric materials that can replace the foam material as the antenna’s lid. While the foam material gives a better result because of its low dielectric constant, it is mechanically weak.
2. Fabricating the flared SBF antenna using aluminum metal to investigate how it compares to the 3D-printed prototype.
3. Conducting more studies on improving the cross-polarization ratio of the antenna. Some of the methods that can be looked into include placing metasurface layers within the antenna cavity and adding parasitic elements to the antenna.

To conclude this chapter and highlight the contributions of this thesis, the presented short backfire antennas was compared in Table 5.1 to a standard gain horn antenna that operates in the C-band [105]. The solid 3D printed SBF antenna has a smaller bandwidth compared to the horn antenna but makes up for it with its much lighter mass which is only about 36.5% of the horn antenna’s mass whilst having a similar gain. The perforated antenna also has a smaller bandwidth than the horn antenna, but it has a higher gain (0.5 dB higher) and lower mass (73% lower). The flared SBF antenna outperformed the standard horn antenna with a 0.7 dB higher gain and 1.15 GHz wider bandwidth while being 33.7% lighter. These antennas are suitable and better replacements for the C-band standard gain horn antenna, especially when low-mass antennas are required.

Table 5.1. A comparison of the C-band standard gain horn antenna to the proposed antennas.

<table>
<thead>
<tr>
<th>Antenna</th>
<th>Gain (dBi)</th>
<th>Frequency range (GHz)</th>
<th>Weight (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard gain C-band horn antenna</td>
<td>15.0</td>
<td>4.9 – 7.05</td>
<td>381</td>
</tr>
<tr>
<td>3D-printed SBF antenna</td>
<td>15.0</td>
<td>4.2 – 5.6</td>
<td>139</td>
</tr>
<tr>
<td>Perforated 3D-printed SBF antenna</td>
<td>15.51</td>
<td>4.1 – 5.6</td>
<td>103</td>
</tr>
<tr>
<td>3D-printed Flared SBF antenna</td>
<td>15.7</td>
<td>4.5 – 7.8</td>
<td>252.5</td>
</tr>
</tbody>
</table>

The research work presented in this thesis highlights the many potentials of additive manufacturing in the fabrication of RF components, especially antennas for space and remote sensing applications. This potential is not only limited to weight reduction as presented in this thesis, but also encompasses the realization of very complex designs that might not have been possible or very difficult to achieve using conventional subtractive manufacturing techniques. The presented enhanced low-mass short backfire antenna also outperforms the C-band standard gain horn antenna and can be easily used as a better replacement in many applications where the horn antenna is employed.
6. References


[31] “Horn Antenna Theory: Equations & Formulas » Electronics Notes.” https://www.electronics-


