Wideband Balun Design with Ferrite Cores

Senior Project
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Abstract

This project explores different balun devices in order to develop a balanced to unbalanced transformer that will operate over a wide bandwidth. The balun must operate from at least 1 MHz (or below) to the highest possible frequency. It must have an insertion loss of less than 1 dB under the ideal case with an imbalance of less than 1 dB and 2.5 degrees. Three balun topologies were tested, each built for a 1:1 impedance transformation ratio. Techniques of measuring each balun topology were investigated including gathering accurate data from a three port device with two port instruments and measuring permeability of magnetic materials. The balun that showed the best results was the Guanella balun wound around 1mm diameter cores from old magnetic core memory matrices. The Guanella balun showed more stable phase difference and insertion loss compared to the other two baluns tested.

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CHAPTER 1

Introduction

Baluns play an important role in today's wireless and radio communications. They are used to transform between balanced and unbalanced transmission lines. Most baluns only work within a narrow frequency range. However, there are applications that require a much broader bandwidth than what common baluns are built for. This project will experiment with different methods of achieving a wide bandwidth. Several balun topologies will be compared in order to find one that will work at a sufficiently large enough bandwidth.

1.1 Context

Transmission lines are the most common way of to communicate an electronic signal from one point to another. A transmission line guides electromagnetic energy and consists of two or more conductors embedded in a dielectric system [Isk00]. Most transmission lines take the form of parallel conductors, coaxial cylinders, or parallel plates, Figure 1.1. Characteristics such as low loss, immunity against noise, and physical space requirements govern which type of transmission line is needed for a specific application.
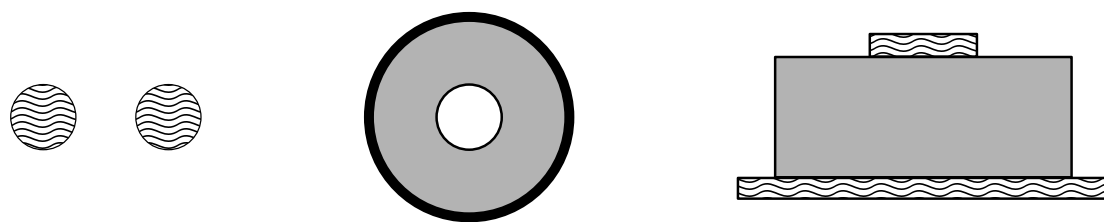
(a) Parallel wires　　　　　(b) Coaxial　　　　　(c) Microstrip line

Figure 1.1: Cross sections of transmission lines.

Antennas are another prevalent way to communicate electromagnetic energy between two or more points. They are used when it is impractical to use a transmission line. An antenna can be thought of as a transmission line of parallel conductors that gradually spreads apart until the separation between the conductors is many wavelengths apart[Kra88]. Generally a transmitted signal will oscillate with time at a specific frequency. A wavelength is the ratio of the phase velocity (e.g. speed of light) of the wave to its frequency. The ends of each conductor stop the current flowing through the transmission line from flowing past the terminations and are instead reflected. However, the electric field between the wires that is inherently induced by the current flow are allowed to escape into free space as seen in Figure 1.2. The antenna guides electromagnetic energy in a certain direction to be received by one or many other antennas. The antenna is a region of transition between a wave guided by a transmission line and a free space wave.
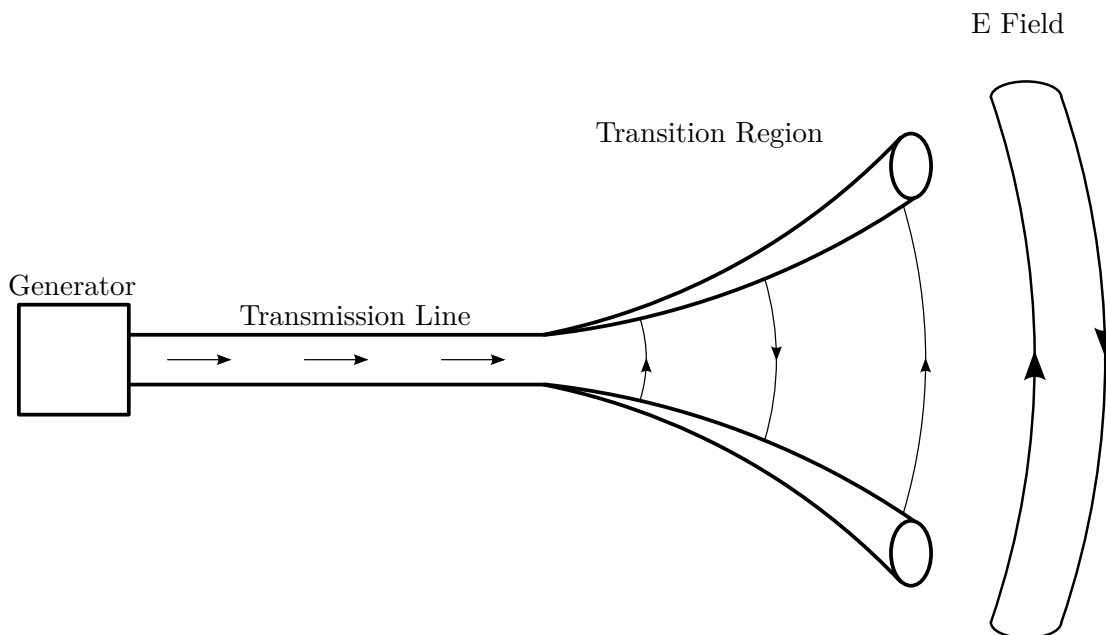

Figure 1.2: Transition of electromagnetic engergy into free space.

The two most popular forms of transmission lines are balanced (e.g. parallel wire conductors) and unbalanced (e.g. coaxial cylinder conductors). There are different advantages with each. Due to the way they operate, most antennas inherently require a balanced current flow that an unbalanced transmission line can't provide. Thus, a balun is required to interface between a device and its antenna when an balanced transmission line is used to connect the them. A balun is a device that transforms between unbalanced and balanced transmission lines. The name balun is derived from

this *bal*anced to *un*balanced transformation. An auxiliary function of a balun is to provide matching between two devices through impedance transformation. Impedance transformation is beyond the scope of this project, so there will be very little discussion on this topic.

1.2 Problem Statement

Most balun devices are built to operate within a very narrow band of frequency. The majority of applications have a very finite frequency of interest with very little frequency bandwidth requirements. As a result, balun construction is relatively easy in that the device only needs to be tuned to work at the frequency of interest. However, there are broadband applications that necessitate the use of a balun that operates over a very wide frequency range. A broadband antenna used in a chirp radar system is an example where a wideband balun would be required. The chirp radar sweeps over a wide range of frequencies over a time period. Other applications include wideband communications protocols or broadband operation on amateur radio.

1.3 Problem Response

In order to facilitate the broadband use of devices, a wideband balun will be developed. The design requirements are itemized below. Since the main operating prinicpal of the balun is the phase difference between the balanced ports, the variation in the phase differnce must be kept to a minimum. Most test equipment has port impedances of 50 Ω, so the impedance at the balun's ports is matched to 50 Ω. Another design decision was to make the balun work at a frequency of at least 1 MHz, since it is difficult to make things sufficiently broadband at higher frequency, since frequency is proportional to the required level of precision.

1.3.1 Design Specifications

This project attempts to design a wideband balun with the following specifications:

- 1:1 impedance transformation ratio
- phase difference of $180° \pm 2.5°$
- imbalance of less than 1dB and 2.5 degrees
- completely passive elements
- frequency range of at least 1 MHz (or below)

1.4 Roadmap

In order to develop an optimal design, theory of balun operation is developed along with consideration of different topologies. Topologies are chosen based on how closely they

should satisfy the desired specifications. Testing the chosen balun topologies requires that testing method is developed in order to accurately compare results. Results of the experimental data are then analyzed to get an idea of how effective each balun is.

CHAPTER 2

Theory

Most transmission lines are unbalanced in nature, such as coaxial cable. A coaxial line consists of an outer shield and a center conductor separated by a dielectric material. Coax transmission lines are more commonly used due to their reduced vulnerability to interference. A balanced transmission line consists of two parallel conductors with equal impedance to ground [Isk00]. Balanced lines have superior rejection to external noise and lower loss than coax lines. Most antennas are required to be fed by or behave similar to a balanced transmission line.

2.1 Balun Theory of Operation

The balun device is used to balance inherently unbalanced systems by canceling or choking off unbalanced current flow. When an unbalanced line is connected to an antenna, such as a dipole, the inner conductor and the outer shield are not coupled equally to the antenna. As seen in Figure 2.1, a current flow I_3 to ground exists on the outer surface of the coax shield [Bal12]. This current flow is inversely proportional to the impedance Z_g of the outer conductor to ground. The difference of I_3 and the current on the inside of the shield I_2 flows through one arm of the dipole, which causes an imbalance with the current flowing through the other arm of the dipole I_1. Inserting a balun between the antenna and the unbalanced line arrests the flow of I_3. The voltage between each side of the dipole and ground are equal in magnitude and 180° out of phase. Thus, the current on the outside of the shield will equal zero.
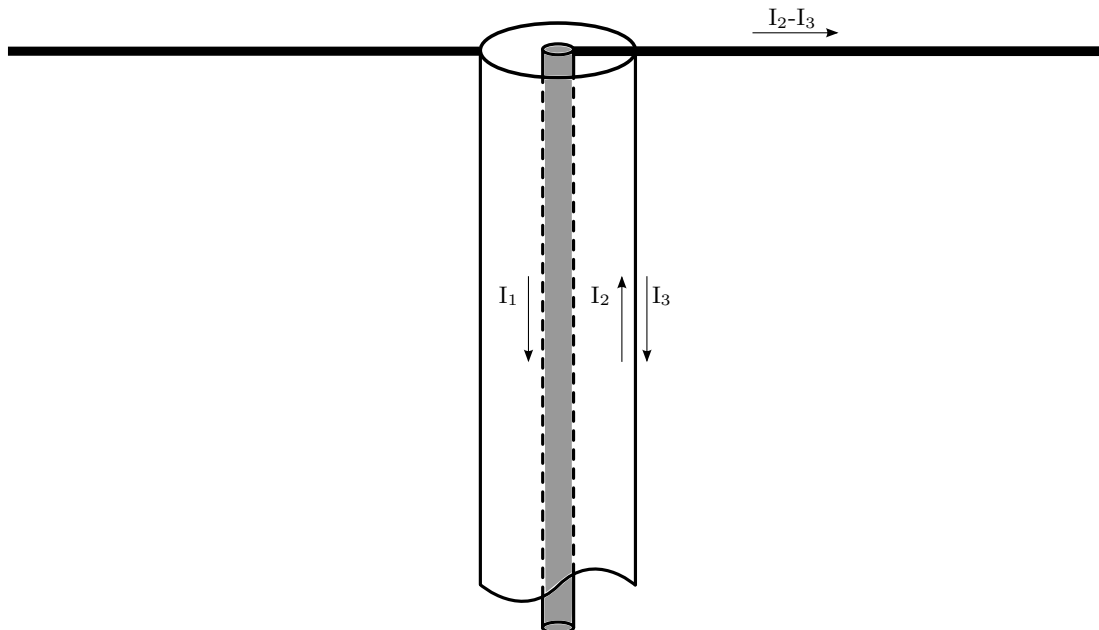
Figure 2.1: Dipole antenna attached to an unbalanced coaxial line.

2.2 Balun Topologies

There are many different strategies for designing baluns, from $\lambda/4$ coaxial baluns to microstrip baluns. Sleeve baluns and microstrip baluns function by making an electrically short path for current to flow in one direction, but an electrically long back if the current tried to flow back in the opposite direction. This is easily acheived by adding a quarter wave open circuit stub to the current path [Bal12]. There are several wideband realizations of baluns using microstrip, such as the planar marchand balun [War12]. Microstrip baluns are not practical at low frequency due to the necessary size of the microstrip. As an example, making a quarter wave stub for 1 MHz would need to be approximately 41 meters long. A better wideband balun for low frequency was ultimately chosen.

2.2.1 Ferrite Core Balun Topologies

Although most balun realizations are narrowband devices, bandwidth can be increased significantly by using ferrite cores in their construction [Sev03]. High decoupling impedance of coils on a ferrite affect the exterior fields on the coax feed line, while the shield's interior fields are unaffected. Thus the line impedance is unchanged on both the center and outer conductors. A bifilar transmission line wound around a ferrite core serves as a broadband common-mode choke, or current balun. Magnetic core material is usually employed at frequencies in the UHF range and below [Bal12]. Such chokes can be quite lossy, and thus their usefulness in the microwave range is greatly diminished.

When loaded with magnetic material, the common-mode structure causes a resistance which generates high ohmic resistance in highly unbalanced antennas. Without the magnetic load, the coils would effectively places an inductance on the common-mode structure. Several different ferrite balun topologies were tested.

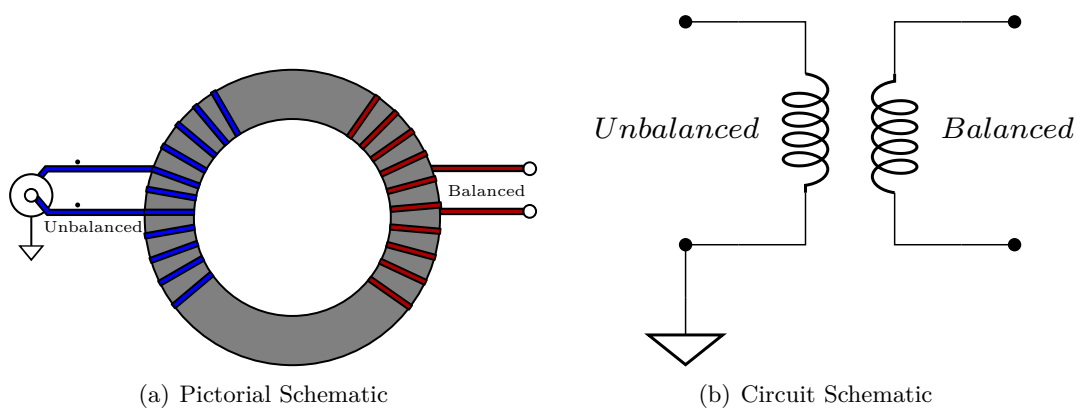(a) Pictorial Schematic   (b) Circuit Schematic

Figure 2.2: 1:1 Transformer Balun

When current carrying wire is wrapped around a toroid of magnetic material, a magnetic current is induced in the core. The magnetic current is largely dependant on the permeability of the material that is used. Permeability is the ratio of the magnetic flux density, **B** to the magnetic field strength, **H**. This relation is non-linear however, and can be represented by a hysteresis loop [Isk00]. When there is a significant increase in the **H** field, there is also an increase in the flux density eventually causing the material to saturate [DeM96]. In saturation, the magnetic flux is impeded by high reluctance, a quantity analogous to resistance. This causes the core to heat up and experience high loses. Thus, permeability is a limiting factor on the lower end of the frequency range. Coils wrapped around the ferrite material can be magnetically coupled to create a transformer type balun, Figure 2.2. There is very little flux circulating through the core outside the main body of the transformer windings.

(a) Pictorial Schematic   (b) Circuit Schematic
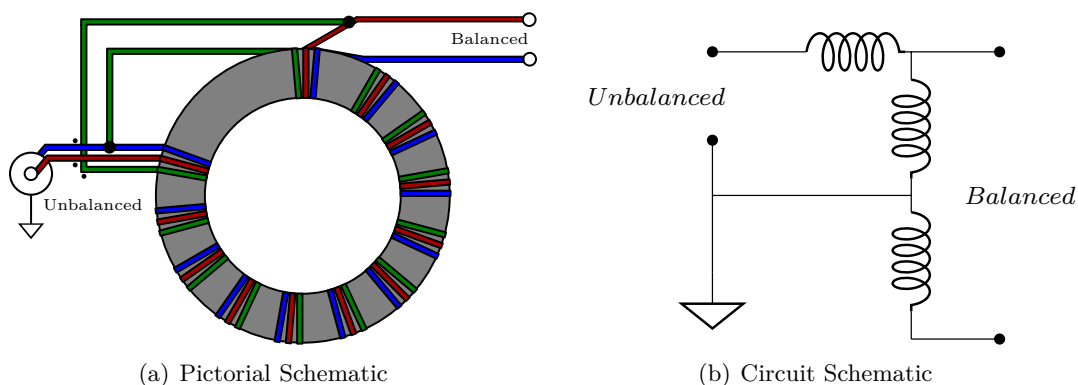
Figure 2.3: 1:1 Ruthroff Balun

Another type of balun, published by C. L. Ruthroff in 1959, is described as a 1:1 broadband transmission balun [Sev03]. This balun configuration uses bifilar windings around a toroid to create a balanced output. A third winding is added in order to complete the magnetizing current, as seen in Figure 2.3. With an equal number of turns as the bifilar windings, the third winding forms a voltage divider with the bifilar pair. This puts each of the balanced terminals at half the voltage of the unbalanced terminal, where one balanced port is positive voltage and the other is negative voltage.

(a) Pictorial Schematic   (b) Circuit Schematic
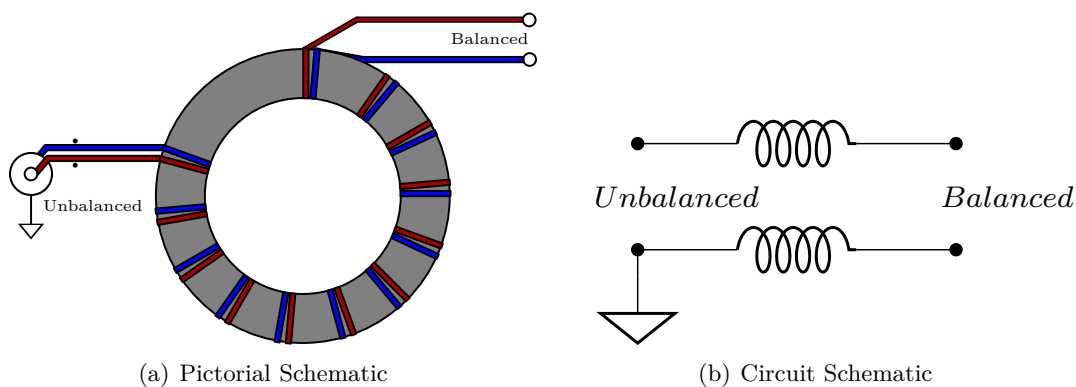
Figure 2.4: 1:1 Guanella Balun

The Guanella balun is similar to the Ruthroff balun with the exception that it does not contain the third winding. The construction of the Guanella balun is comparatively simple, Figure 2.4. In 1944, G. Guanella showed that only transmission line currents were allowed to flow without respect to where the ground was placed on the load [Sev03]. Given that the topology has enough choking reactance, the output is isolated from the input. Like the Ruthroff balun, the voltage of the unbalanced line is split inversely among the two balanced terminals.

CHAPTER 3

Experiments

3.1 Balun Construction

The balun devices were initially built using a kit supplied by Amidon, but the materials that Amidon supplies are too low in permeability to make effective baluns for wide bandwidths. Small 2.5mm diameter cores were obtained by dissecting a microwave mixer from Mini-circuits. 1mm diameter cores were also acquired from old stock magnetic core memory matrices. Because the cores were so small, tweezers and a magnifying glass needed to be used to wind them accurately, Figure 3.1. Forty gauge wire was used in order to wind the cores.

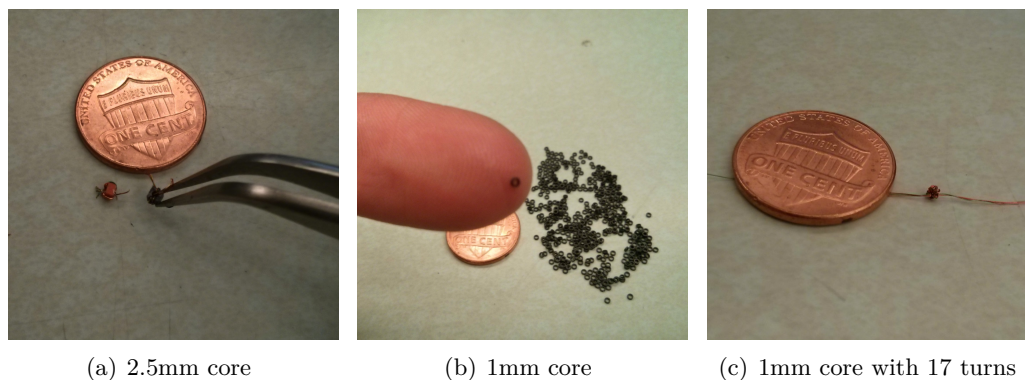(a) 2.5mm core   (b) 1mm core   (c) 1mm core with 17 turns

Figure 3.1: Tested Ferrite Cores

Cores were wound in the balun configurations discussed in the previous section, then mounted to a testing fixture so they could be connected to a vector network analyzer (VNA) for measurement. First, a test fixture was constructed using semi-rigid coax and a special breakout board to make the balun easier to mount as seen in Figure 3.2. This method created non-idealities in measurements, so a new test fixture was constructed

using only semi-rigid coax and a ground plane. This method was much harder to mount
to and required extra time and dexterity. Great care was taken to assure that each
semi-rigid coax line was exactly the same length as the others so that an accurate
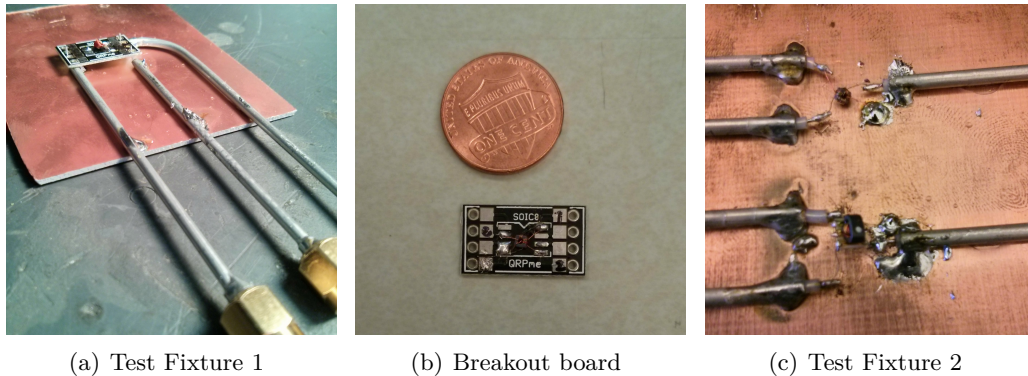referance plane shift could be made with the VNA.

(a) Test Fixture 1   (b) Breakout board   (c) Test Fixture 2

Figure 3.2: Test Fixtures

3.2 Measurement Techniques

Several measurements techniques to obtain the S-Parameters were used. Different
techniques for measuring the core permeability were also explored.

3.2.1 Three Port Measurements

The available VNA that would go to a low enough frequency was only capable of mea-
suring two port devices [12], so alternate methods of measuring a three port device were
required. S-Parameters were taken with a well defined load attached to each terminal
[JOH82][DRO83]. These S-parameter measurements were then applied to a set of linear
equations in order to obtain the full set of S-parameters [Eri13]. A MATLAB script
(Appendix A.1) was then written in order to make the equations easier to calculate and
plot. Unfortunately, this method is very sensitive to noise. While it gave good results,
it did not satisfy the resolution requirements of this project.

Other methods were ultimately used, such as taking measurements with a 50Ω termination
at each unused port. A three port VNA with a minimum frequency of 10 MHz was used
when it became apparent that a certain topology could not reach a lower frequency.

3.2.2 Material Permeability Measurements

Since the magnetic core material used for testing was not characterised, a technique for measuring core permeability was investigated. Neither of the core material had documented permeability. A MATLAB script (Appendix A.2) was developed in order to calculate the permeability of a test material from S-Parameters. The testing method required a test fixture, seen in Figure 3.3, to test the inductance of 1 turn around the core. This method uses a single turn inductor with a parallel-series resistor to ground [Jin05]. This method did not yeild very acurrate results when tested with a ferrite core of known permeability. This is probably due to the high level if precision that the test required and the small size of the core.
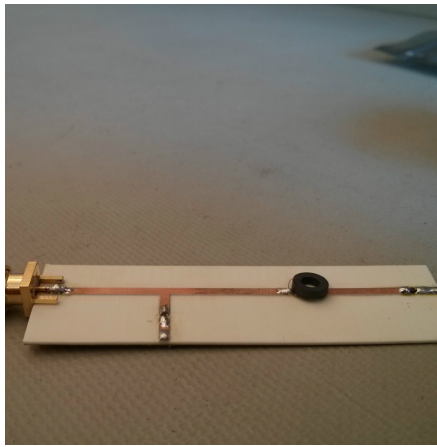

Figure 3.3: Permeability Fixture

CHAPTER 4

Results

4.1 Transformer Balun Results

The performance of the Transformer Balun was the least impressive. The commercial balun that was acquired from minicircuits (Part No. TC1-1TG2+) barely worked over the frequency that it was advertised to work at. The transformer balun has a center tap on the balanced terminations to connect to ground. Supposedly, the connection to ground would improve performance. However, no such increase was seen.

4.1.1 Transformer Insertion Loss

The insertion loss of these baluns were extremely poor. There wasn't much difference between the insertion loss of the baluns with grounded taps, Figure 4.1, versus ungrounded taps, Figure 4.2. The insertion loss stayed under -10dB over most of the freuquency range. A slightly better S21 insertion loss is seen in the ungrounded baluns, but they are still well under ideal.
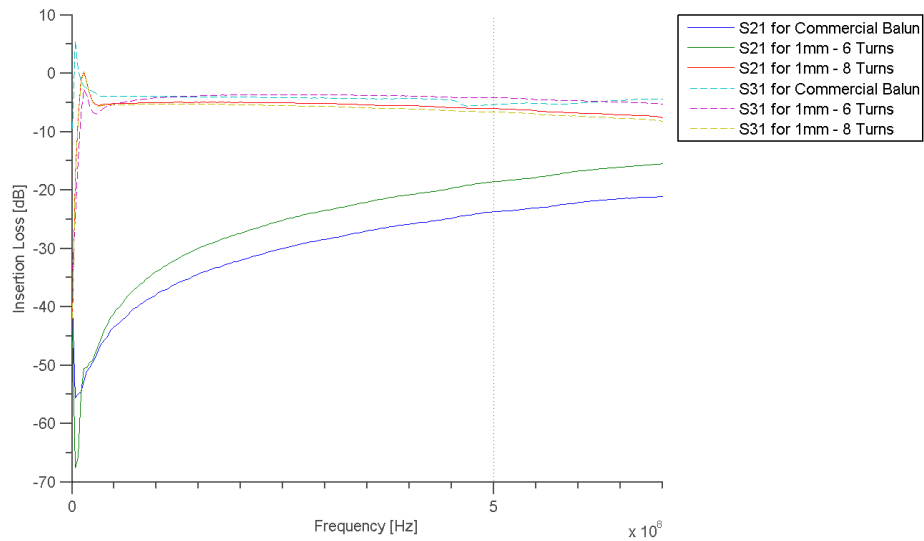
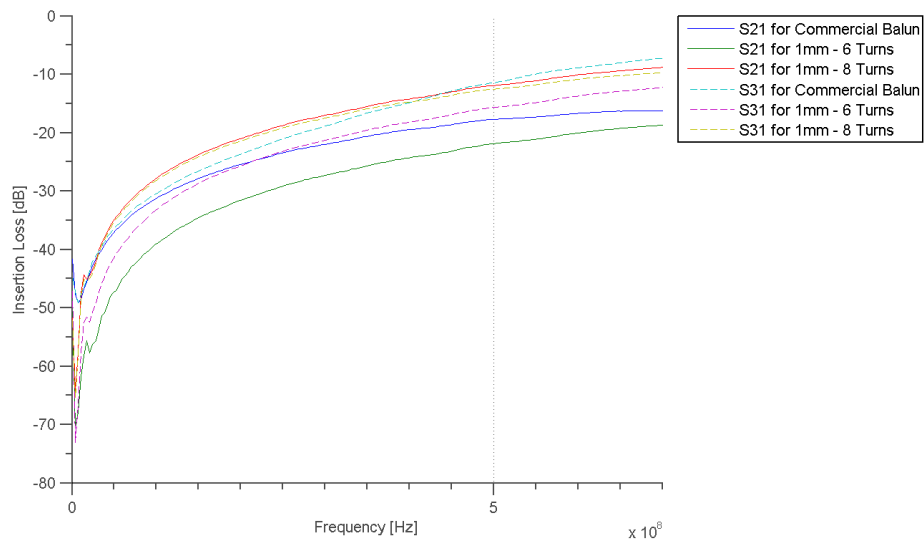Figure 4.1: Grounded Transformer Insertion Loss vs Frequency.

Figure 4.2: Un-grounded Transformer Insertion Loss vs Frequency.

4.1.2 Transformer Phase Difference

The phase difference was pretty disappointing in these baluns. While some of them showed a somewhat steady phase difference in the grounded tap case, they did not have the necessary difference of 180°. The commercial balun had a phase difference of approximately 180 at around 1 MHz, Figure 4.4, but it steadily increased as the

frequency increased. The un-grounded commercial balun functions as a balun, but it is very narrowband.
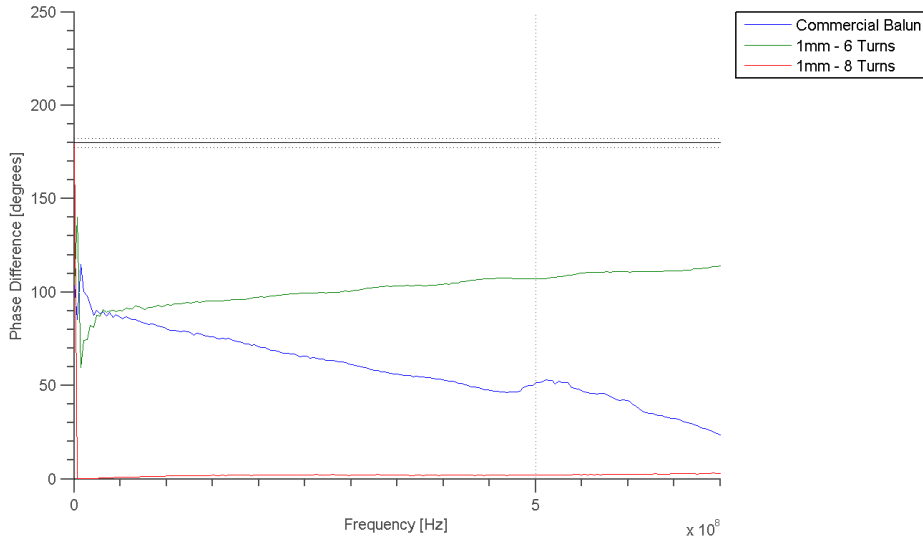

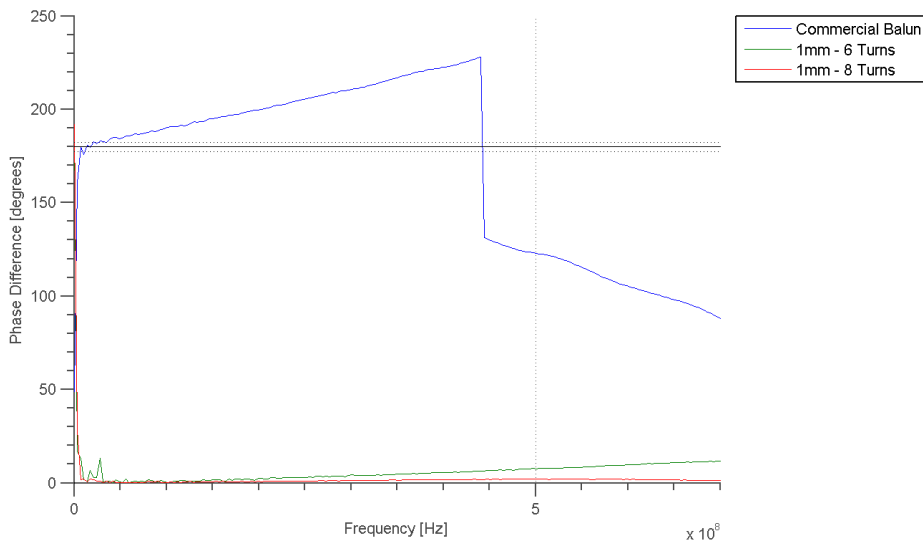Figure 4.3: Grounded Transformer Phase Difference vs Frequency.

Figure 4.4: Un-grounded Transformer Phase Difference vs Frequency.

4.2 Ruthroff Balun Results

The Ruthroff Baluns did not perform very well either. These baluns are supposed
to function over a very wide bandwidth. However, the phase difference between the
balanced terminals was erratic, especially in the case of the 2.5mm diameter cores. The
insertion loss was a little better than the transformer balun, but not by much.

4.2.1 Ruthroff Insertion Loss

The 2.5mm diameter cores proved to be very lossy with this topology. The insertion loss
in Figure 4.5 changed a lot with respect to frequency with good areas only periodically.
The 1mm diameter baluns had a much smoother insertion loss curve, although for the
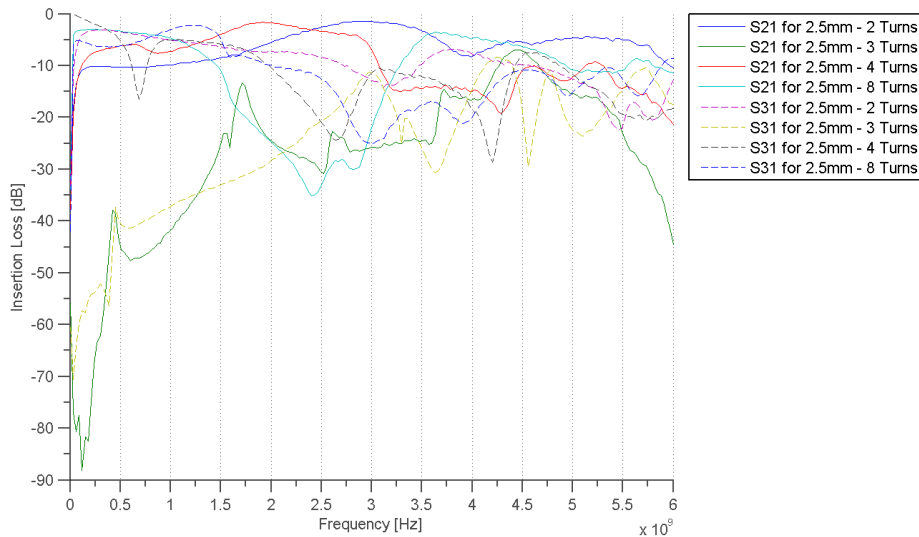most part the insertion loss was still bad.

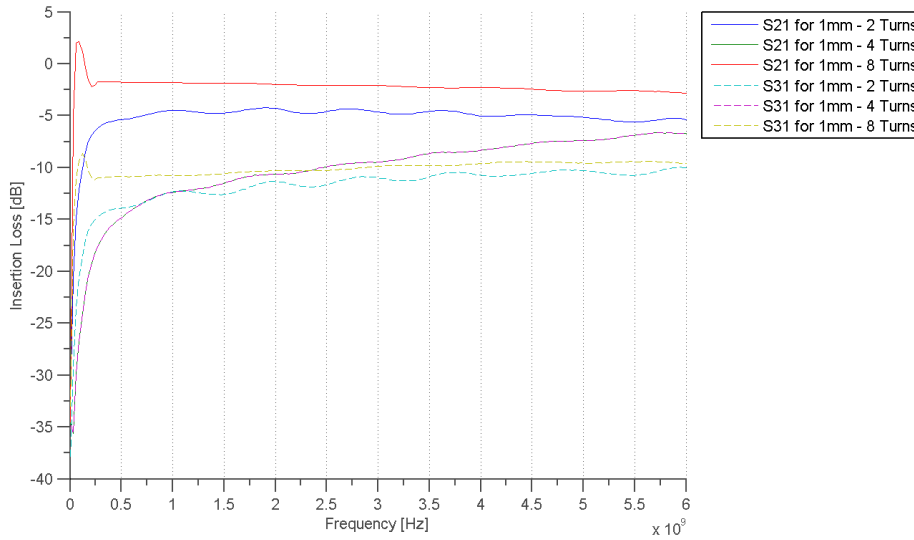Figure 4.5: 2.5mm Ruthroff Insertion Loss vs Frequency.

Figure 4.6: 1mm Ruthroff Insertion Loss vs Frequency.

4.2.2 Ruthroff Phase Difference

The phase difference of the 2.5mm diameter cores changed drastically over the frequency range, Figure 4.7. None of the variations had a phase difference that was very close to 180°, with the exception of the two turn variation between 1 MHz and 500 MHz. There was nearly no phase difference seen in the 1mm diameter balun variations, Figure 4.8.
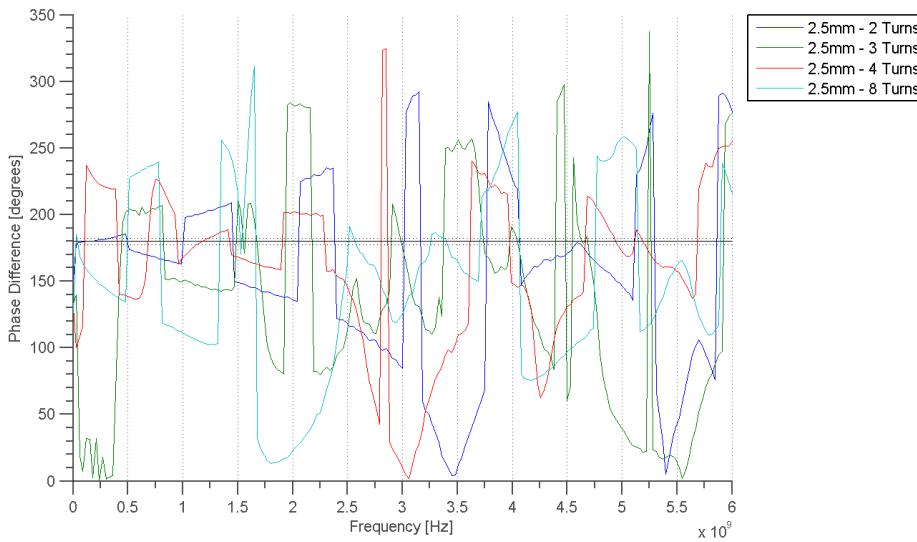

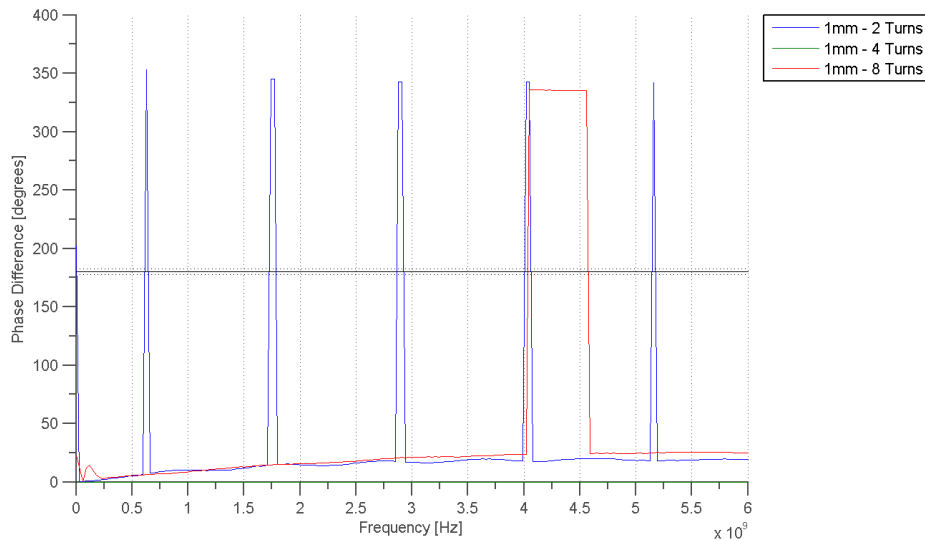Figure 4.7: 2.5mm Ruthroff Phase Difference vs Frequency.

Figure 4.8: 1mm Ruthroff Phase Difference vs Frequency.

4.3 Guanella Balun Results

The results of the Guanella Balun topology was by far the most impressive of the lot. The S-parameter measurements appear to oscillate, however this is caused by a slight variation in the line length between the VNA and the device under test. A good approximation can be made as to where the actual S-parameters lie on the plots through extrapolation.

4.3.1 Guanella Insertion Loss

The insertion loss seen by these baluns were surprisingly good, and in some cases ideal. The ideal loss through each balanced port should be -3 dB, because the voltage from the unbalanced port is being split between the balanced terminals. The Guanella baluns with fewer turns seemed to suffer less from insertion loss, while the higher turn baluns, Figure 4.11.
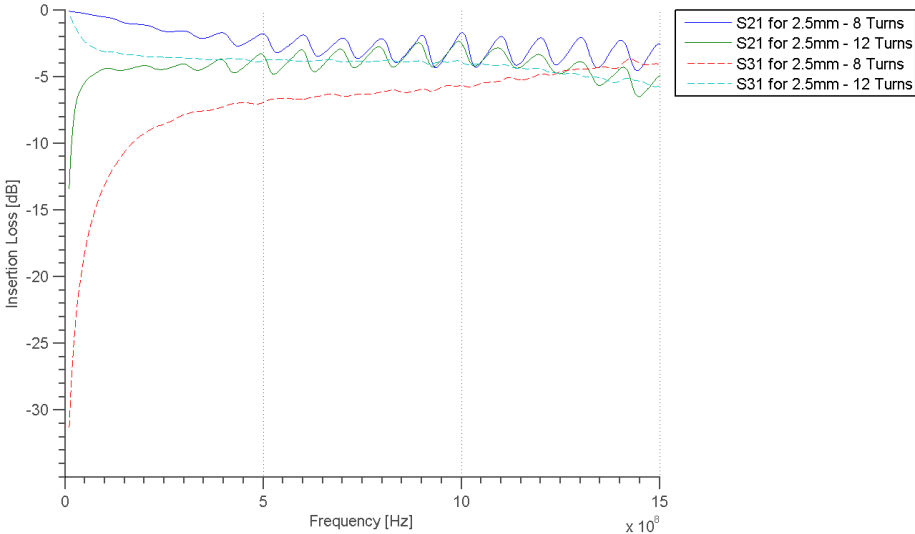
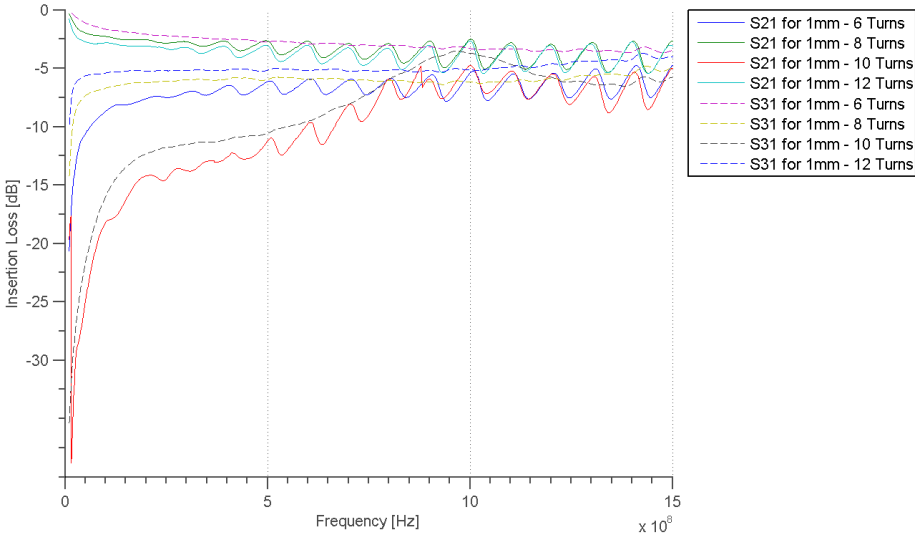Figure 4.9: 2.5mm Guanella Insertion Loss vs Frequency.

Figure 4.10: 1mm Guanella Insertion Loss vs Frequency.
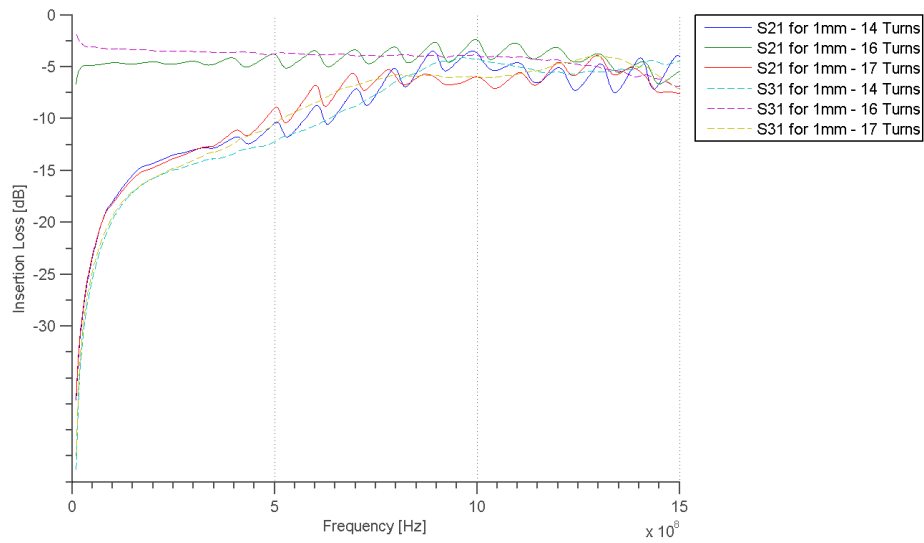
Figure 4.11: 1mm Guanella Insertion Loss vs Frequency.

4.3.2 Guanella Phase Difference

The phase difference between the balanced terminals were very close to the ideal 180°. There is a large improvement in the phase difference from the 2.5mm to the 1mm diameter balun variation. The higher turn variations, Figure 4.14, were very tight around the ideal phase. Most of the variations were able to keep a good phase difference for over 1 GHz of bandwidth.
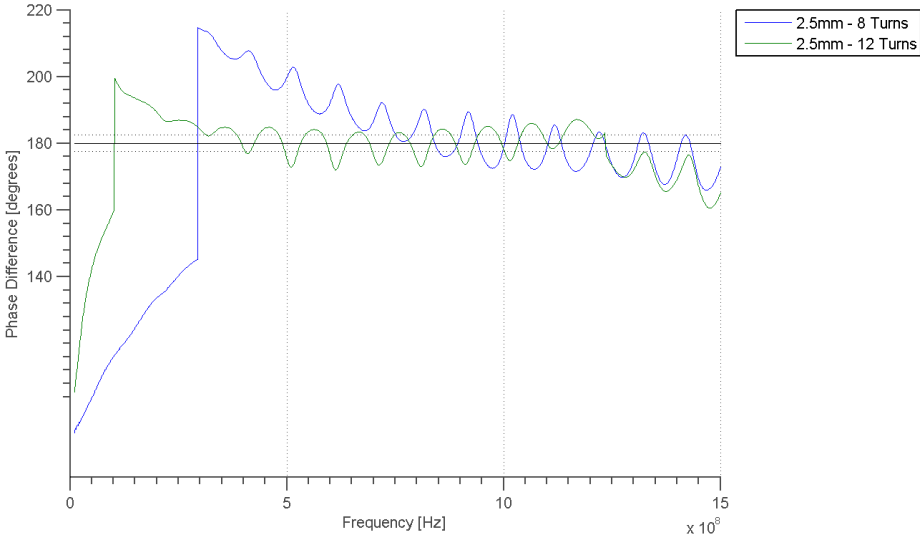
Figure 4.12: 2.5mm Guanella Phase Difference vs Frequency.
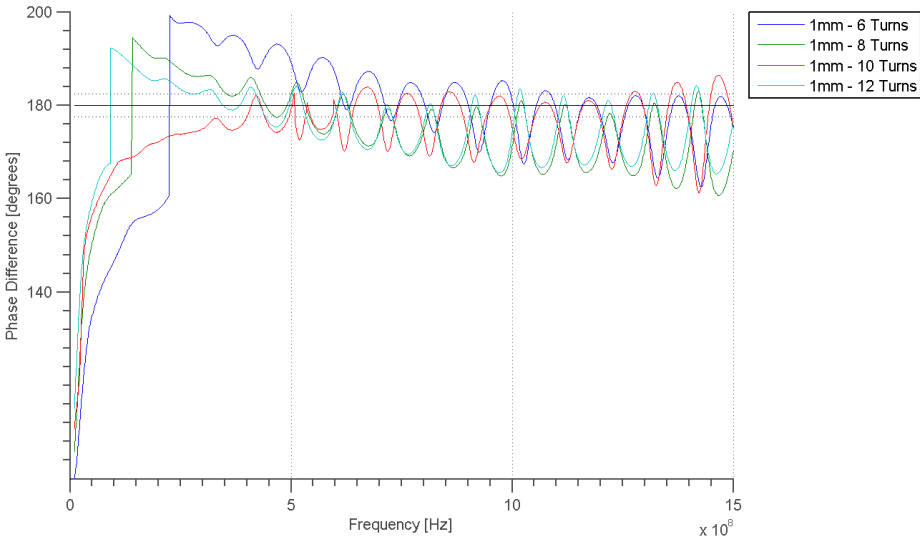
Figure 4.13: 1mm Guanella Phase Difference vs Frequency.
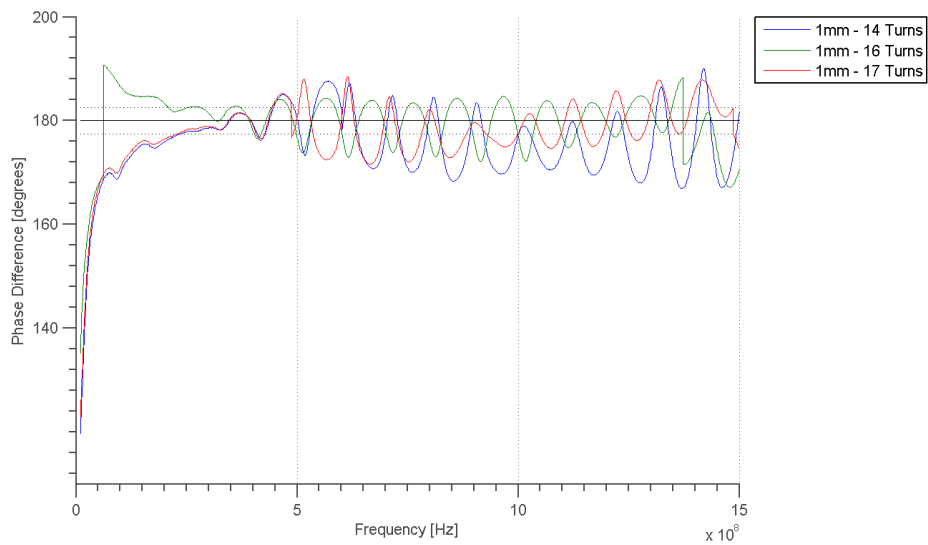
Figure 4.14: 1mm Guanella Phase Difference vs Frequency.

4.3.3 Guanella Impedance Transformation

The impedance transformation is only shown in the Guanella topology beacuse the other topologies largely did not function as baluns. The ideal impedance transformation ratio outlined in the specifications was 1. The 2.5mm diameter variations had less than 1 transformation ratio over much of the band, Figure 4.15. The 1mm diameter baluns only showed to have a good impedance transformation after 500 MHz, with the higher turn baluns doing much better.

Figure 4.15: 2.5mm Guanella Transformation Ratio vs Frequency.

Figure 4.16: 1mm Guanella Transformation Ratio vs Frequency.
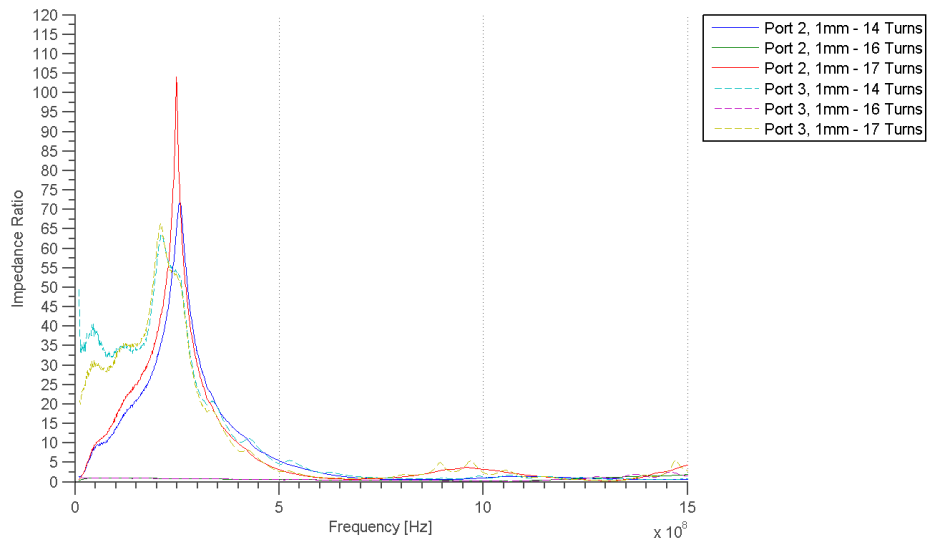
Figure 4.17: 1mm Guanella Transformation Ratio vs Frequency.

CHAPTER 5

Summary and Outlook

This project was successful in showing that ferrite cores can be used effectively to make wideband baluns. Although many of the specs were not met, the project came very close with the Guanella balun realization. The phase difference 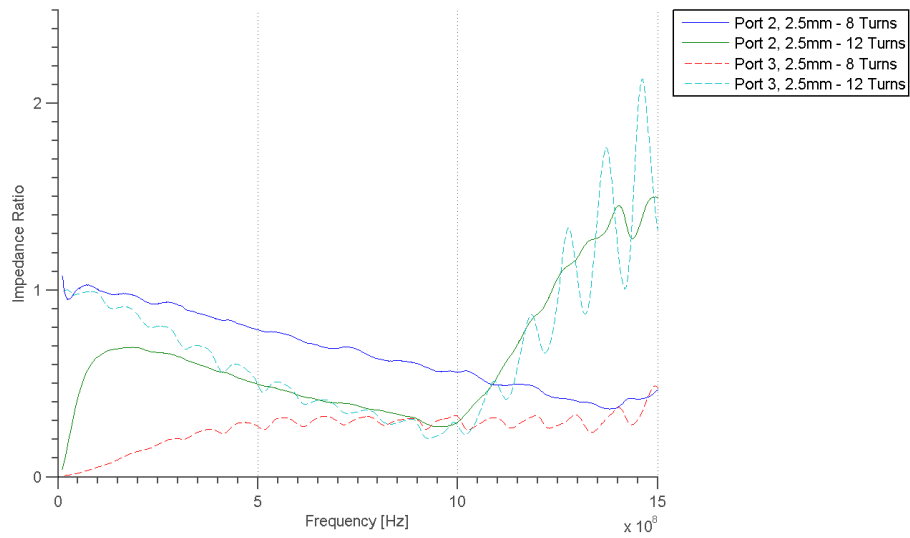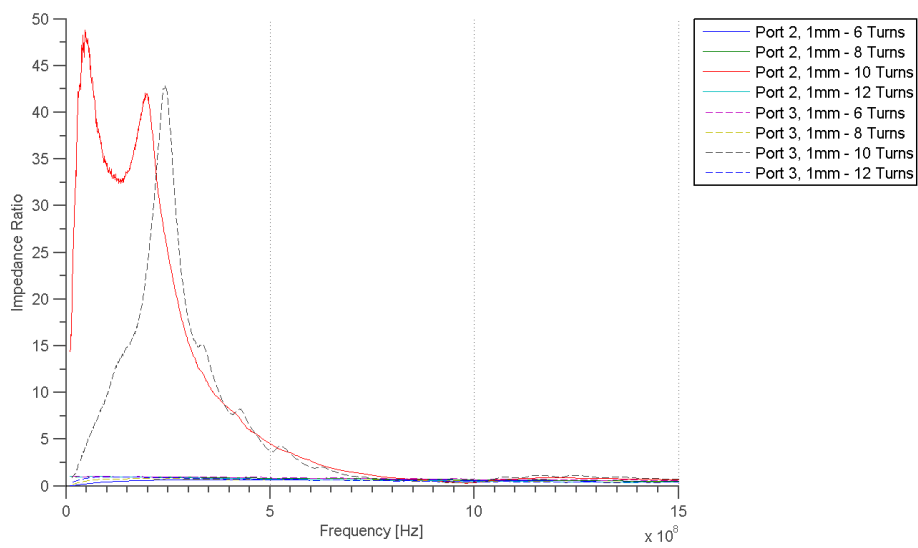was just outside the desired range, and the impedance transformation ratio was very close to 1. A lower frequency bound of 1 MHz was not achieved, though with tuning it was plausable. In future development, it would be a good idea to attempt to improve the functional frequency range by getting more uniform windings around the toroid. This would also greatly improve the reflection at the input ports and the insertion loss.

Different methods of measurement were also explored. Several forms of measurement were used to gather and verify S-Parameter results. This was especially difficult since the balun is a 3 port device. It was also difficult to determine the permeability of material without proper testing equipment. Even when alternate methods were applied, it proved difficult to get successful measurements. For future work on this project, a better measurement fixture could be manufactured in order to get more consistent results.

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         2003 (cit. on pp. 6, 8).

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            John Wiley & Sons, 2012 (cit. on p. 6).

List of Figures

APPENDIX A

Code

A.1 MATLAB Code: 2 Port to N Port Conversion

```matlab
%{
  Paul Biggins
  Electrical Engineering, Cal Poly SLO
  April 2014

  This script reads multiple 2x2 two port S Parameters
  and normalizes the matrices in order to create a
  3x3 set of S Parameters for a 3-port device.
%}

pname = ['P12' 'P13' 'P23'];
mLayout = [1 1 2; 1 1 3; 2 3 2]; %matrix layout for testing purposes
magPhase = ['M' 'P'];
title = ['Magnitude' 'Phase'];

function [sParam, freq, gammaVector] = buildMatrix

  s11Name = strcat(pname(mLayout(1,1)), 'S11', magPhase(k), '.csv');
  s12Name = strcat(pname(mLayout(1,2)), 'S12', magPhase(k), '.csv');
  s13Name = strcat(pname(mLayout(1,3)), 'S13', magPhase(k), '.csv');
  s21Name = strcat(pname(mLayout(2,1)), 'S21', magPhase(k), '.csv');
  s22Name = strcat(pname(mLayout(2,2)), 'S22', magPhase(k), '.csv');
  s23Name = strcat(pname(mLayout(2,3)), 'S23', magPhase(k), '.csv');
  s31Name = strcat(pname(mLayout(3,1)), 'S31', magPhase(k), '.csv');
  s32Name = strcat(pname(mLayout(3,2)), 'S32', magPhase(k), '.csv');
  s33Name = strcat(pname(mLayout(3,3)), 'S33', magPhase(k), '.csv');

  s11 = csvread(s11Name, 8, 0);
  s12 = csvread(s12Name, 8, 0);
  s13 = csvread(s13Name, 8, 0);
```

```matlab
31    s21 = csvread(s21Name, 8, 0);
32    s22 = csvread(s22Name, 8, 0);
33    s23 = csvread(s23Name, 8, 0);
34    s31 = csvread(s31Name, 8, 0);
35    s32 = csvread(s32Name, 8, 0);
36    s33 = csvread(s33Name, 8, 0);
37
38    load1 = csvread(strcat('Load1', magPhase(k), '.csv'), 8, 0);
39    load2 = csvread(strcat('Load2', magPhase(k), '.csv'), 8, 0);
40    load3 = csvread(strcat('Load3', magPhase(k), '.csv'), 8, 0);
41
42    sParam = [s11 s12 s13;
43             s21 s22 s23;
44          s31 s32 s33];
45    freq = s11(:,1);
46    gammaVector = [load1(:,2) load2(:,2) load3(:,2)];
47 end;
48
49 function parameterPlot
50
51    figure;
52    subplot(3,3,1);
53    plot(freq, sParamNorm(1,1));
54    title(strcat('Port 1 Return Loss (S11, ', title(k), ')'))
55
56    subplot(3,3,2);
57    plot(freq, sParamNorm(1,2));
58    title(strcat('Reverse Insertion Loss (S12, ', title(k), ')'))
59
60    subplot(3,3,3);
61    plot(freq, sParamNorm(1,3));
62    title(strcat('Reverse Insertion Loss (S13, ', title(k), ')'))
63
64    subplot(3,3,4);
65    plot(freq, sParamNorm(2,1));
66    title(strcat('Forward Insertion Loss (S21, ', title(k), ')'))
67
68    subplot(3,3,5);
69    plot(freq, sParamNorm(2,2));
70    title(strcat('Port 2 Return Loss (S22, ', title(k), ')'))
71
72    subplot(3,3,6);
73    plot(freq, sParamNorm(2,3));
74    title(strcat('Balanced Port Isolation (S23, ', title(k), ')'))
75
76    subplot(3,3,7);
77    plot(freq, sParamNorm(3,1));
```

```matlab
78    title(strcat('Forward Insertion Loss (S31, ', title(k), ')'))
79
80    subplot(3,3,8);
81    plot(freq, sParamNorm(3,2));
82    title(strcat('Balanced Port Isolation (S32, ', title(k), ')'))
83
84    subplot(3,3,9);
85    plot(freq, sParamNorm(3,3));
86    title(strcat('Port 3 Return Loss (S33, ', title(k), ')'))
87 end
88
89 for (k = 1:2),
90
91    [sParam, freq, gammaVector] = buildMatrix;
92
93    for (row = 1:size(freq,1)),
94
95      gamma = diag(gammaVector);
96      sParamNorm = inv((eye(3) - sParam)) * (sParam - gamma) * inv((eye(3) -
   sParam * gamma)) * (eye(3) - sParam);
97      %sParamVector(row,:) = reshape(transpose(sParamNorm),1,[]);
98    end;
99
100   parameterPlot;
101 end;
```

A.2 MATLAB Code: Measurement of Material Permeability

```matlab
1 %{
2    Paul Biggins
3    Electrical Engineering, Cal Poly SLO
4    May 2014
5
6    This script reads S11 parameters and calculates
7    the initial permeability of a ferrite core.
8 %}
9
10 clear;
11 %dimensional parameters
12 a = 0.0000799; %wire guage [m]
13 b = 0.0005; %distance from wire to core ID [m]
14 c = 0.00142 + b; %distance from wire to OD [m]
15 e = c + 0.001; %distance from wire to outside loop [m]
16 h = 0.0015; %high of core [m]
```

```matlab
17 h0 = 0.00253; %hight of loop [m]
18
19 s11 = csvread('FT-23-67perm.csv', 8, 0);
20 gamma = 10.^(s11(:,2)/20);
21 freq = s11(:,1);
22 omega = freq*2*pi();
23
24 for (row = 1:size(freq,1)),
25   %calculate load impedance from s11
26   Z_L(row,1) = -50*(gamma(row,1) + 1)/(gamma(row,1) - 1);
27
28   %calculate input impedance from load impedance
29   Z(row,1) = -200*(Z_L(row,1) - 50)/(Z_L(row,1) - 100);
30
31   %calculate self inductance in air
32   u0 = 4*pi()*10^(-7); %permeability of air
33   L_air = u0*h0/(2*pi())*log(e/a);
34
35   %calculate permeability
36   u(row,1) = (2*pi()*(Z(row,1) - i*omega(row,1)*L_air))/(i*omega(row,1)*u0*h*
   log(c/b)) + 1;
37 end;
38
39 %plot permeability
40 figure;
41 plot(freq, u);
42 title('Core Permeability vs Frequency');
```

APPENDIX B

Senior Project Anaylysis

B.1 Economic

The economic impacts of the project vary widely. The human labor that goes into this project begins far before the build and design process. When commercially produced parts and raw materials are acquired, there is human labor needed to build and produce the parts, labor needed to maintain the establishments that there parts were acquired from, and work needed for the components to be delivered. Not only does this employ those directly involved with handling parts, but it indirectly impacts those services that are connected. An example, when components are shipped from a distribution center, there are economic impacts to each community that the truck must drive through. The truck puts wear and tear on roads it drives on and emits carbon discharge into the atmosphere. This requires labor to maintain both the roads and the environment. Sometimes taxes are paid when ordering parts and benefit other local governments and cash flow ultimately leaves from the place where the final product will be assembled and manufactured. Another consideration is the test equipment that is used to design the final product. The tools needed to test often have the same economic impact as the raw materials themselves. They also require outside maintenance in order to keep them working.

The bulk of the project will require basic components in order to build a final product. It will also include test and measurement tools. All measurement tools and resources will be borrowed at no cost from Cal Poly's Electrical Engineering Department. Since this is a non-commercial application, the remaining project costs will be personally expensed. The project costs are calculated by using the project design schedule to estimate the approximate time needed to complete labor and parts costs from similar published projects.

Due to the non-commercial nature of the competition, there will be no monetary profits made from the final product. However, the results of the project may benefit others with educational value at the completion of the project. When the project concludes, others may use it as reference in order to complete similar products. This

cuts down on research time and ultimately maximizes profits of others.

B.2 Commercial Production

There are no plans on making this project commercially available since the purposes are for research. If balun design was manufactured on a commercial basis, however, the final design would be very easy to build since it would contain as few components as possible. The constraint on components would also mean that the final product could be produced cheaply from widely available materials. The cost to build would be a fraction of the original build process since there would be no testing or research involved. The bulk of the cost would be from parts. This device is not in high demand since, for most specialty applications, they are built by those who need them instead of commercially obtained. The manufacturing price for such a device would be around \$90, and the purchase price for a consumer would be approximately \$100. Since the balun is completely passive, the only recurring costs are negligible to no maintenance costs.

B.3 Environmental

The environmental impact of my balun design will mainly be associated with manufacture and production. There are many environmental considerations even before manufacture begins. The natural materials needed to create some of the components are becoming increasingly scarce as electronics become more prevalent in our daily lives. When components are disposed of, they are often not recycled properly. As a result, most electronic waste pollutes the environment. There are also impacts from shipping and producing the components. This affects any community that is indirectly and directly involved in the project. Since the balun is completely passive, it will not consume energy external to the inputs. In testing and building the end product, the tools will use a lot of electricity. Minimization of environmental impacts is difficult to achieve since they are usually much more expensive. Thus, this project won't take environmental impacts into consideration since it is beyond its scope.

B.4 Manufacturability

An auxiliary goal of the project is to keep the balun as cheap and simple as possible. It will be challenging to build the balun in a way that is easy for someone who is repeating or building upon these results to reproduce. Since I will be trying to use discrete components, it will be difficult to get matched components or those that are within necessary tolerances. Sometimes it is difficult to find the parts needed from the available distributers. It will be difficult to find other or equivalent components if the

needed parts are unavailable.

B.5 Sustainability

The completed balun will be relatively static, assuming that it is well insulated from the elements in a proper chassis. Since it is completely passive, it will not need very much maintenance unless the chassis fails to prevent damage from nature or user mistreatment. The weakest points of the balun will be at the female SMA ports. Coaxial (or similar) cable is very sensitive to moisture, so the junction between the inputs and outputs would be the primary point of failure.

Although the balun does not demand any external resources to drive it, other than the input signal, it does require resources to build. The construction of the balun will likely need many raw materials such as copper, silicon, and ferrous chokes. The use of raw materials is not ideal, since most electronics are not recycled. Further refinement of the final product would include developing a way to use recycled components in the design. Another significant upgrade would be to make a weather-proof chassis to prevent failure and early breakdown of the balun.

B.6 Ethical

There are several ethical considerations that must be made with this project. Since this project is based on a research, I am obligated not to seek outside help to complete my design. It would also be unethical to use any commercial designs or components. Using commercial sources to build a balun would defeat the purpose of the research project. All design techniques and decisions should be made by me, otherwise external sources should be cited and given credit. It is unclear if the project design could be carried over to commercial applications. Applying my design to commercial ends would probably unethical because by putting the design in the Cal Poly Digital Commons, it is in the public domain.

This concern seems to be reflected in the IEEE Code of Ethics. Taking a design from a competition and using it in a commercial environment seems like a conflict of interest. Since there is no monetary gain that comes out of this project, it is safe from unethical practices such as bribery or malicious actions against competitors. Most of the other ethical practices outlined by the IEEE are involved with sharing and accepting knowledge with the technological community. Similarly, the ACM Code of Ethics calls for the contribution of honest information with society without harming them [16]. Both organizations highlight giving credit to the intellectual property of others when it is due. My project seeks to cite references as necessary.

B.7 Health and Safety

As stated in both the IEEE Code of Ethics and the ACM Code of Ethics , the project will avoid harm to others and adhere to safe practices when testing and designing. A safety concern during the design process is using test equipment properly. Safe and procedural handling of all test equipment should be observed to avoid bodily injury. Some test equipment has the potential to cause a health risk if used improperly. The proper use and handling of the end product is also a concern. If the balun isn't packaged in a weather resistant chassis, it could cause a user to become shocked or damage to occur to connected equipment.

B.8 Social and Political

The largest social impact that my project will have is the spread of knowledge to others who have a similar project. Hopefully, my final design and data will be useful to someone who is designing a similar balun. Since this largely a design project, the data will be very valuable for educational purposes. Parts manufacturers and distributers will also be indirectly impacted in that they will be able to gauge what kind of parts people are looking for based on the needs of my project. Another indirect stakeholder is the group of engineering students that I am competing against. They will be both negatively and positively benefited from my project.

B.9 Development

In carrying out this project, I learn many new analysis techniques. Most notably, I gained a much better grasp of how to use to vector network analyzer as a tool to aide in the design of my balun. I also learned to use valuable software and project management tools. I gained a much better knowledge of RF and EM theory through the research I have done for this project. Please reference the bibliography 5 for sources of literature that were used in this project.