RECONFIGURABLE LIQUID METAL ALLOY ANTENNAS EMBEDED

IN STRUCTURAL COMPOSITES

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Reconfigurable Liquid Metal Alloy Antennas Embedded in Structural Composites

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The design and excitation of a liquid metal alloy antenna embedded into structural composite panel is studied. The alloy resides in micro-channels embedded into the composite that allows it to be pumped in and out of the panel to form the electrical paths necessary for the antenna. The antenna geometry is a derivative of a zig-zag log periodic dipole wire antenna. The excitation of the antenna from a structurally embedded printed microstrip transmission line is also examined. The operational bandwidth and frequency response are reconfigured by altering the amount of alloy in the meandering structure of the channels.

ACKNOWLEDGMENTS

NOMENCLATURE

LPA   Log Periodic Antenna

TL   Transmission Line

VSWR   Voltage Standing Wave Ratio

S-parameter   Scattering Parameter

S_{ij} S-parameter: the power inputted at port i and outputted at port j ratio

TRL   Thru, Reflect, Line

LMA   Liquid Metal Antenna

SMA   Sub-Miniature Version A

Ga:In   Gallium Indium 75.5:24.5 weight percent

FR4   Flame Retardate grade 4 epoxy substrate

PLA   Tin (II) Oxalate Catalyzed Polylactic Acid

CHAPTER I

INTRODUCTION

Broadband antennas and their advantages

Broadband antennas are highly advantageous in the field of communications because it expands the frequencies that can be transmitted or received with a single antenna; thereby, making it frequency independent. One common broadband antenna is the log periodic antenna. This type of antenna is designed in such a way that over a set period the radiation characteristics and impedance repeat logarithmically with respect to frequency [1]. The main parameters that determine the frequency band are size, growth rate, and aperture angle [2]. The particular geometry that will be further studied is the zig-zag wire log periodic dipole antenna. This type of antenna is simple to design and has a similar performance to other of periodic antennas [1].

Liquid metal for reconfigurable antennas

The use of liquid metal alloy for an antenna is a recent development in the field of electromagnetics. Liquid metal has been used in a variety of ways including: flexible patch antennas [3] and tunable monopoles [4]. The benefit of liquid metal in an antenna is that it reduces the error caused by mechanical moving parts and increases the reconfigurability of the antenna. Combining liquid metal alloy with the wide band characteristics of the LPA will give an optimal antenna design inside of a structural composite that is both wide band and reconfigurable. The liquid metal alloy used was eutectic gallium-indium (Sigma-Adrich) with a composition of 75.5% Ga and 24.5% In (by weight).

THE ANTENNA GEOMETRY

Log-Periodic Antennas

The first geometry explored is the zig-zag LPA. The design is feed in the center of the substrate

and then zig-zags out on both the left and rights sides following the parametric equations:

$$X(t) = \tan\left(\frac{\alpha}{2}\right)\frac{L\tau^t}{2} \qquad (1)$$

$$Y(t) = \tan\left(\frac{\alpha}{2}\right)\frac{L\tau^t}{2} \qquad (2)$$

where L is the length of the substrate, τ is the growth rate, and α is the aperture angle. In this and

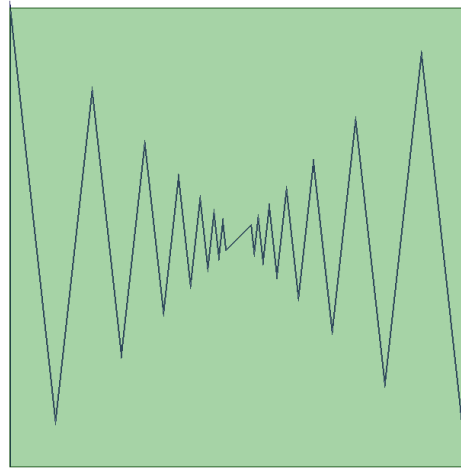all future designs, τ is 0.8 and α is 90° Figure 1 show the initial zig-zag design.

Figure 1. Zig-Zag geometry following the parametric equations for 0≤t≤13

In addition to this design, the equations can be modified to make trapezoidal zig-zag geometry. The advantage to this is the angles where the channels change direction are less severe which will be better for pumping the liquid metal through the channels. This is achieved by adding ab additional line segments so that there are horizontal lines connecting each of the corners where t is an integer. The final design is shown in figure 2.
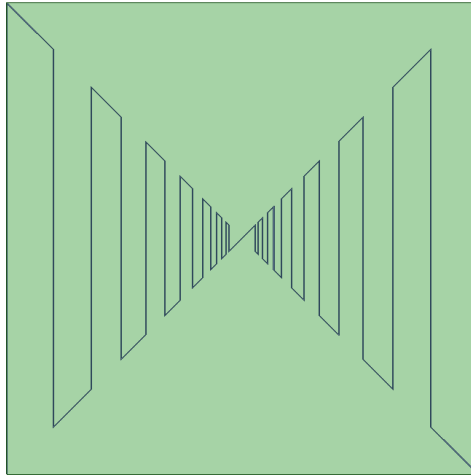

Figure 2. The trapezoidal tooth zig-zag design for τ=0.8 and 0≤t≤13

The trapezoid tooth design still has sharp angles that will impede the liquid metal as it is pumped into the channels. In addition, when the panels are fabricated, the parallel channels are in line with the orientation of the fabric mesh and this can cause problems in the integrity of the channel (a discussion on the manufacturing of the panel is discussed later). Ideally, the channels need to be smooth curves and not sharp angles; therefore, a modified sinusoidal curve is used. Again, this geometry is formed by two parametric equations:

$$X(t) = \tan\left(\frac{\alpha}{2}\right)\frac{L\tau^t}{2}\left|\cos(\pi t)^{S-t}\right| \qquad (3)$$

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$$Y(t) = \tan\left(\frac{\alpha}{2}\right)\frac{L\tau^{t}}{2} \qquad (4)$$

where S is the slope change exponent. The purpose of the constant S is to once again limit the change in slope to allow the liquid metal to flood the channels without being obstructed. Figure 3 shows the sinusoidal design.
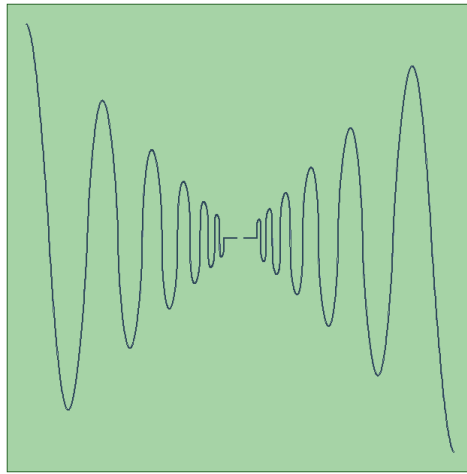

Figure 3. The sinusoidal tooth zig zag for τ=0.8 and 0≤t≤11

Although the sinusoidal design is less effective than the original zig-zag, the design meets the constraints of the angles needed for the liquid metal and still maintains the LPA behavior.

The entire length of the channels is about 3 m in a 30 cm by 30 cm square. This creates a problem with evacuating the channels to form the hollow channels in the manufacturing process. In order to solve this problem, the antenna is downsized from a 30 cm by 30 cm square to a 15 cm by 15 cm square. The final parametric equations with the inputted values for each parameter are given by:

$$X(t) = 68.75mm * 0.8^t \cos(\pi t)^{1.2^{-t}} \qquad (5)$$

$$Y(t) = 68.75mm * 0.8^t \qquad (6)$$

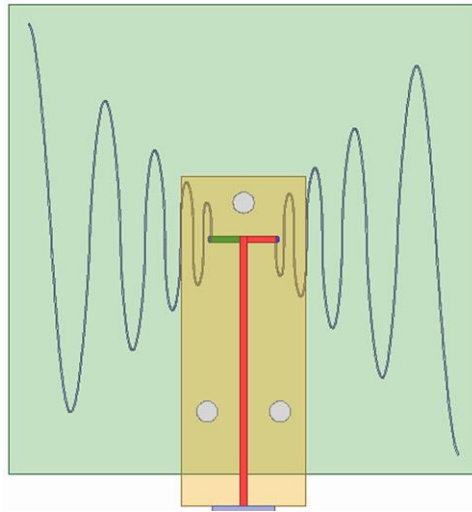Figure 4. The sinusoidal tooth zig zag for τ=0.8 and 0≤t≤9

Figure 4 shows the new smaller design with the feeds structure in place. The two sinusoidal arms are separated by 40 mm and each is connected to either the ground or signal of the transmission feed structure (this will be discussed in more detail in the next chapter.)

Log Periodic Antenna Simulation

The antenna design was constructed and simulated in Ansoft's HFSS The design was simulated at a center frequency of 3 GHz and used a parametric sweep on the variable *t*, from 0 to 9 with a step size of 1. This gave ten states, three of which are shown in figure 5, of the antenna to demonstrate the reconfigurability as the Ga:In is moved throughout the antenna.
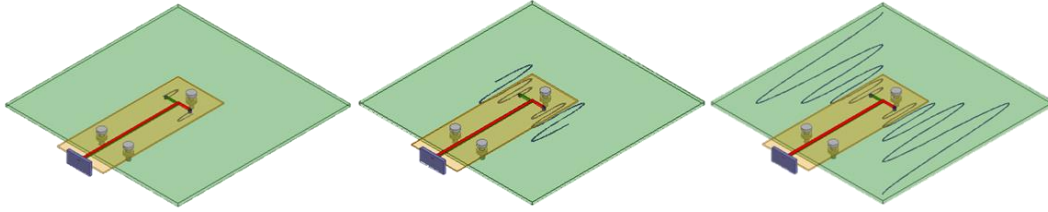
Figure 5. State 1 (left), State 5 (middle), and State 9 (right) of the LMA

The S_{11} parameter of all the states is shown in Figure 6. As the Ga:In in the channel increases so does the length of the dipole. This in turn shifts the operating frequency down, there is an inverse relationship of frequency of operation to length of the dipole.
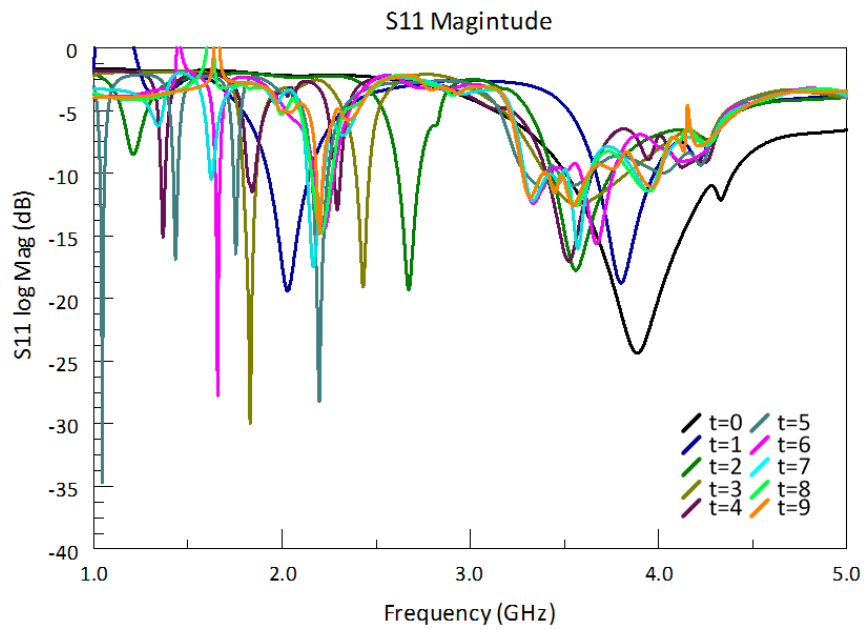

Figure 6. S_{11} for the Sinusoidal LPA

CHAPTER III

THE TRANSMISSION LINE

Transmission Line Design

Now that the design for the antenna is finalized, the LMA must be excited in order to transmit or receive. The antenna needs to have a feed structure that is wideband, minimizes reflection, and is impedance matched. A balun transforms an unbalanced source, in this case the coaxial cable to excite the antenna, into a balanced source, in this case the antenna is balanced [5]. In this case, a microstrip transmission line will act as a balun to transform the signal from the coaxial cable to the center of the antenna. The purpose of matching the TL to the LPA is to reduce the amount of power that is reflected and therefore wasted. A matched TL and antenna pair will be more efficient when radiating. The feed network will reside on the plane of the composite to minimize unwanted interference, coupling, and blockage. Three designs will be discussed.

Tapered Microstrip Transmission Line

A microstrip TL consists of a line that is on a substrate with a ground plane underneath. Traditionally, a microstrip line has a set width that is determined by the substrate's dielectric, the frequency of operation, and input impedance. However, this antenna needs to operate over a range of frequencies. Both the ground plane and microstrip line are tapered to achieve the desired wideband performance, as seen in figure 7.
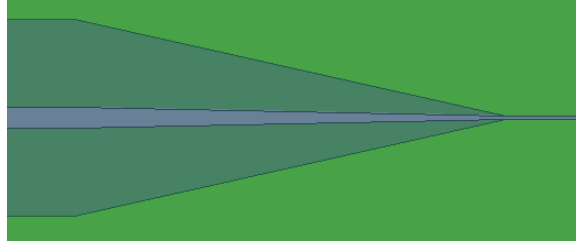
Figure 7. Tapered Microstrip TL, the dark grey is on the bottom of the substrate and the purple is on top of the substrate

This design does have some frequency dependencies and does not operate well at lower frequencies, 10 MHz to about 1 GHZ. The TL has high reflection (S_{11} and S_{22}) in this range (more than 10 %,) as seen by figure 8. For this reason another broad band TL will be explored.
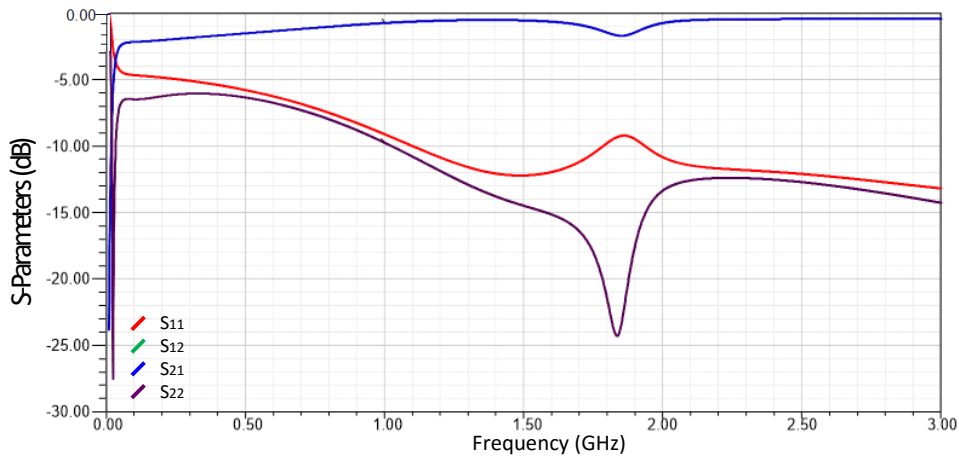

Figure 8. Tapered Microstrip TL S-Parameters

Exponential Tapered Microstrip Transmission Line

The exponential tapered TL utilizes a ground plane that is exponentially tapered. This results in a frequency dependent TL, which is desirable for this application [6]. The wider the base of the structure, the more dramatic the exponential curve is and the better performance. However, this makes the feed structure very large, which means more interference with the actual antenna.
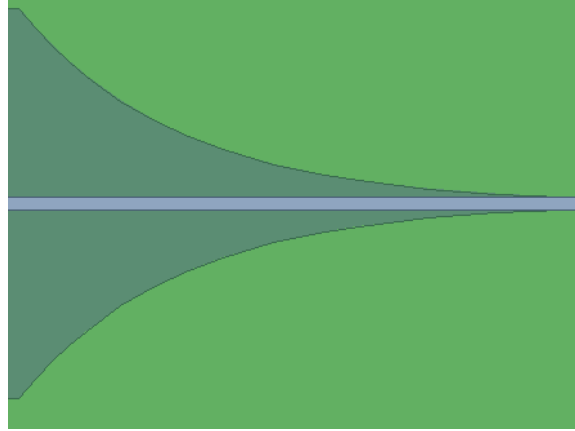
11

Figure 9. Exponential Tapered Microstrip TL, the dark grey is on the bottom of the substrate and the purple is on top of the substrate

This feed design does operate better than the previous design discussed. As seen in figure 10, both S_{11} and S_{22} are below -15dB for the entire bandwidth tested. In addition, both S_{12} and S_{21} hover around zero, signifying that the structure is transmitting well. However, the size of the board the feed structure is on does create a problem and a smaller design is explored.
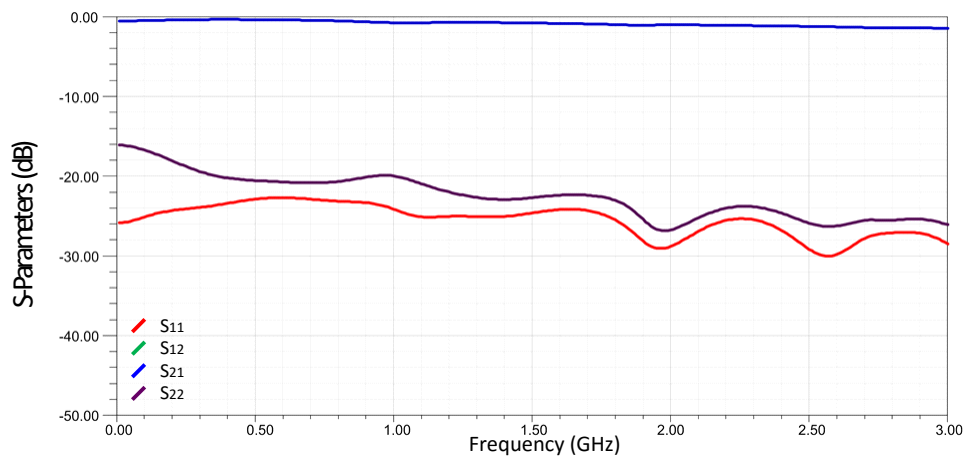

Figure 10. Exponentially Tapered Microstrip TL S-Parameters

Parallel Strip Transmission Line

The Parallel Strip TL consist of two lines that sit on top of the other with a substrate in between, in this case FR4. The top line is the signal and the bottom is the ground. This design is advantageous because of its smaller design and wide band characteristics.

Figure 11. Parallel Strip TL, the dark grey is on the bottom of the substrate (not shown) and the purple is on top of the substrate

As seen below, both the S_{11} and S_{22} are below -35dB for the entire bandwidth tested. In addition, both S_{12} and S_{21} hover around zero, signifying that the structure is transmitting well. This TL works better than the previous designs and is smaller, which makes it easier to attach to the LMA panel.
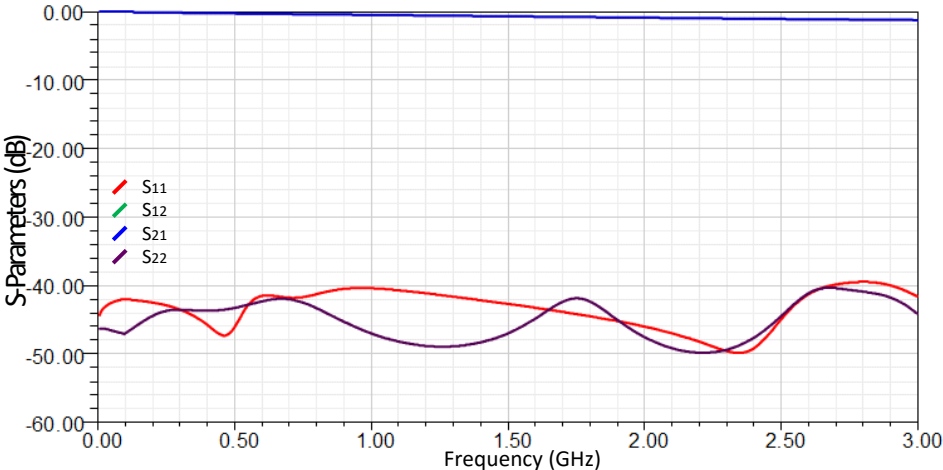

Figure 12. Parallel Strip TL S-Parameters

Integration of the Transmission Line

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A parallel strip microstrip line will act as a balun to feed transmit the excitation from the coaxial cable to the center of the antenna. The feed network will terminate in an antipodal dipole will come off of either end of the feed line that will be used to excite the embedded channels of the LMA. The dipole will then be attached to channels using copper vias (this will be explained in further detail in the next chapter.) The feed network will be constructed on FR4 with copper milled into the desired line widths for both the TL and the dipole.
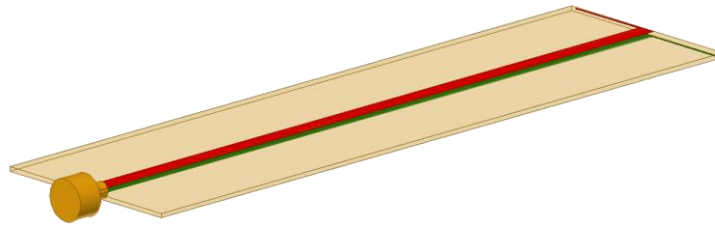

Figure 13. Coaxial-fed parallel strip feed line with antipodal dipole, the green is on the bottom of the substrate and the red is on top of the substrate

CHAPTER IV

RESLUTS

Final Fabrication

Panel Design

The partners at the Air Force Research Laboratory used the following technique to create the structural composite with the microvascular channels. The desired antenna geometry was 3D printed using VascTech, a tin (II) oxalate catalyzed polylactic acid. The design was printed in a single pass (0.05 mm line thickness) onto a Kapton sheet. The Kapton sheet served as a build surface during the printing and as a transfer sheet for the composite panel layering. The full ply stack consisted of eight epoxy/quartz fabric prepreg plies (RM-2014/4581 Astroquartzr III Fabric,) each 2.24 mm thick. The laminae were flat stacked in a quasi-isotropic $[-45/90/+45/0]$s sequence. After the first four plies were laid, the Kapton transfer sheet hosting the printed sacrificial template was inverted and the PLA template was thermally transferred (i.e., ironed) onto ply four; a thin cotton cloth was used as a buffer between the iron and the Kapton. Once adhesion between the template and fourth ply was confirmed, the Kapton sheet was removed and the remaining four plies were sequentially laid, completing the laminate. An outer vacuum bag was prepared and a modified autoclave cycle was used to initially cure the composite. After cure, the panels were trimmed with a wet diamond saw to a final dimension of 152 mm squared.
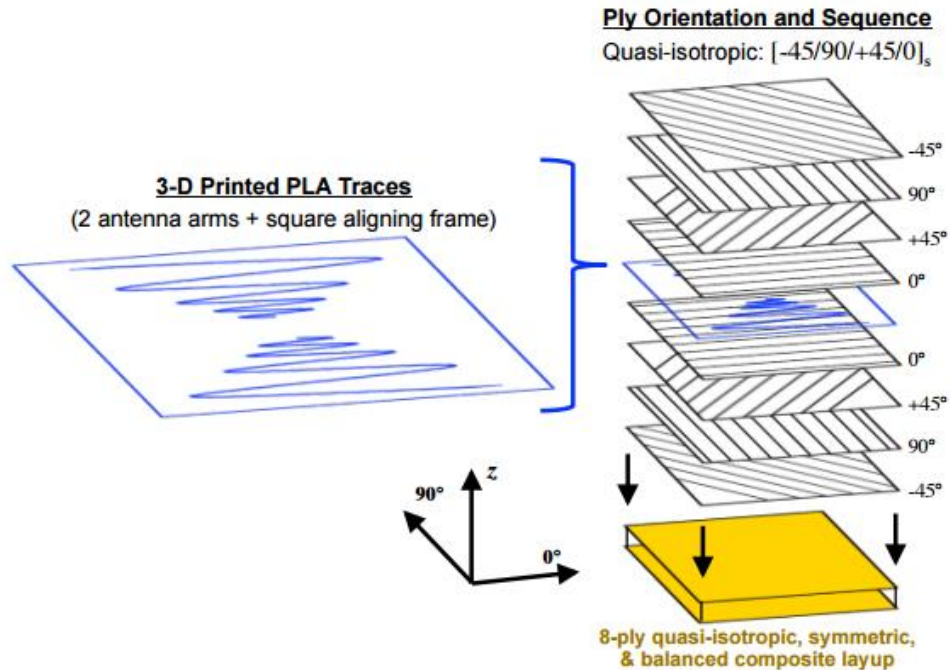
Figure 14. Description of the woven composite laminate layup configuration: Traces of PLA fabricated using a 3-D printer are placed at the mid-plane of an eight-ply, quasi-isotropic, symmetric, and balanced laminate

Testing Apparatus

The LMA panel will have the parallel line feed attached using nylon screws. When the transmission line reaches the center of the Arlon substrate, both the ground plane (bottom of FR4) and the microstrip line (top of FR4) end in two separate lines that go in opposite directions of the feed to form an antipodal dipole. Vias are placed at either end of the dipole to form a connection from the transmission line to the antenna.
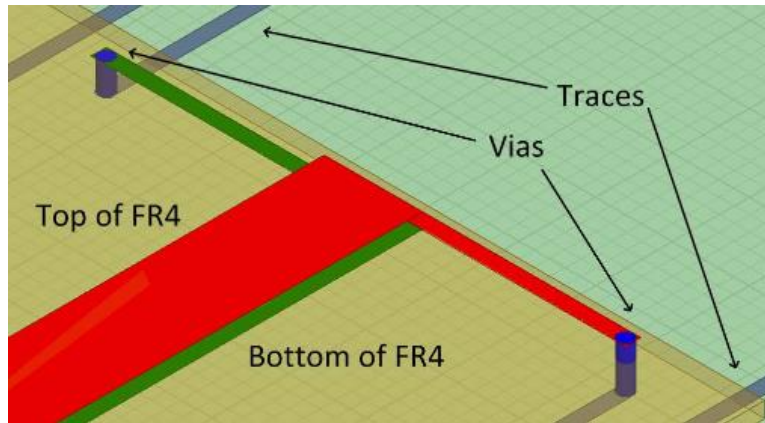
Figure 15. Copper on FR4 connected with vias to the antenna traces

In order to pump the liquid metal alloy into the composite, the setup in figure 16 is proposed. The top half of the via will have a copper tube inserted and soldered to the dipole. The liquid metal will then be inserted through a tube that is in connected with the copper before flooding the channels. This will allow the feed to be properly connected to the feed structure.
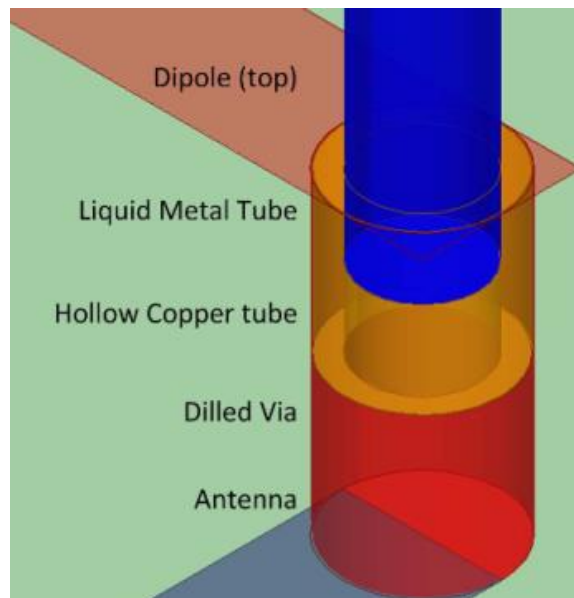

Figure 16. Proposed design to pump liquid metal in the antenna channels

Syringes filled with Ga:In will then be inserted in both of the vias to control the amount of metal that is inserted and extracted. The panel will rest on a platform with a light that will illuminate the board and show the channels. Figure 17 shows the test set up without the syringes.
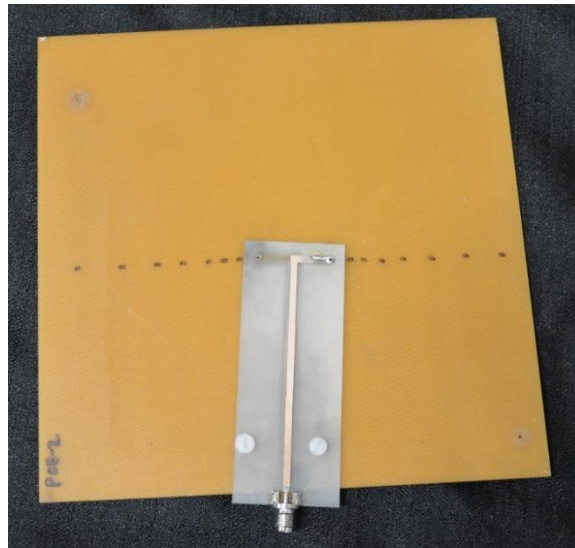

Figure 17. Astroquartz panel with evacuated channels for the LMA with parallel strip feed line with antipodal dipole attached

Measured Results

TRL Calibration

The TRL calibration uses three standards (thru, reflect, and line,) to solve for the error coefficient when using a network analyzer [7]. The TRL calibration accounts for transition effects due to the coax-microstrip connection and allows you to set a reference plane some distance along the feed line. The TRL kit must be designed for the same substrate and characteristic impedance of the device under test; therefore, the TRL will be built using the same FR4 material as the feed line with the structural composite attached [7].

The reference length, (open circuit reflect standard length) will be the same as the length of the parallel strip feed, 86.075 mm [8]. This is the de-embed length for all measurements. The zero-length thru is twice the reflect length, 172.15 mm [8]. When the two ports are attached to the thru standard, there will be no measured line length between the two ports because the reflect length is the de-embed length. The line length should be between is longer than the thru standard and between 20° and 160° of phase, (used to determine the lower and upper frequency bound respectively) [8]. The line standard has an additional length of a quarter wavelength centered at 3 GHz that is added to the thru standard length, 184.87 mm.

Figure 18. LMA (left), Reflect standard (top middle), Line Standard (bottom middle), Thru Standard (right)

Each of the parallel strip feeds for the TRL are milled out on 31 mil FR4. They are then attached to the Astroquartz panel using nylon screws, chosen for their minimal effects on the behavior of the antenna. The SMA connectors are attached to the ends of each standard and the network analyzer is calibrated for the LMA testing. The current TRL is for a frequency range of 1 GHz to

5 GHz. The TRL constructed does not adequately eliminate all the error in measurement. A new TRL with a larger band width (250 MHz to 5 GHz) with less error is undergoing construction.

Impedance Testing

The LMA will be tested at each state for the S_{11} parameter, or the reflection coefficient. This will show how well the impedance is matched and how efficient the antenna is. The LMA has 10 states representing the number of half periods of the sine are filled, ranging from 0 (no Ga:In) to 9 (completely filled with Ga:In). Because of problems with the construction of the channels, the channel had a clog that impeded the flow of the metal. This resulted in the LMA leaking Ga:In and only state 0 and state 1 being tested.

Figures 19 and 20 show the results for the first two measured states of the LMA. Both have measured results that align with the simulated S_{11} parameter. The effect of the faulty TRL calibration are apparent in the state 0 plot. The S_{11} parameter cannot be above 0 dB, as it is from about 2.3 GHz to 2.4 GHz, because that would violate the law of conservation of energy. A better TRL calibration would remove this error and would also alight the measured results with the simulated results with higher fidelity.
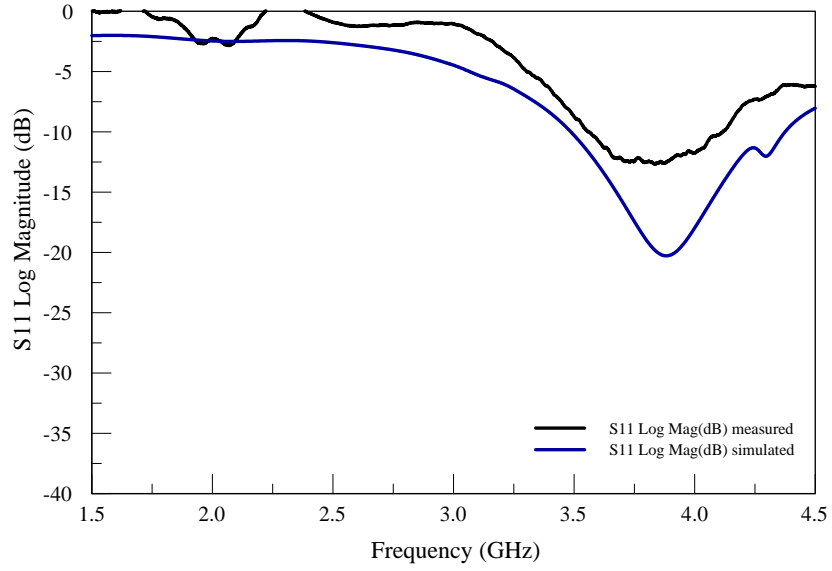
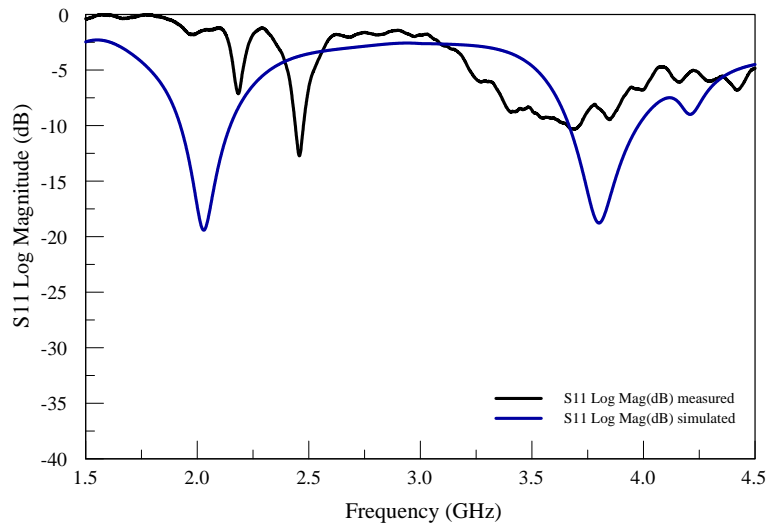Figure 19. Measured and simulated S_{11} results for state 0

Figure 20. Measured and simulated S_{11} results for sate 1

CHAPTER V

CONCLUSION

Interpretation of Results

In this work, the physical operation and computational analysis of a reconfigurable liquid metal-based sinusoidal LPA embedded into a proven aerospace structural composite was demonstrated for the first time. The preliminary results of the antenna, both simulated and measured, show that it is reconfigurable at a variety of frequencies in the 1 GHz to 5 GHz range. It was further demonstrated that a novel feed structure could be designed, built, and integrated that satisfies both liquid mass transfer and electromagnetic energy transfer requirements.

Future Work

The future work will consist of a better testing apparatus and TRL calibration for the current antenna geometry. New panels will be made with wider channel widths to reduce the probability of impeded channels for further testing. In addition, other variations of the sinusoidal LPA will be considered to achieve a superior frequency reconfigurability.

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