Part C Individual Project
Final Report

Name: Obaleke Ayomipo Oyindamola

ID Number: B517241

Programme: Electronic and Computer Systems Engineering

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Supervisor: James Flint

Project Title: Liquid Metal Antennas – monopole antenna

Abstract:

An experimental study of a reconfigurable monopole antenna that's designed using safe liquid metal to measure various frequencies at different heights of the liquid metal in an acrylic tube. The antenna proposed in this study is operated in the UHF range (340MHz -1GHz), it is used for high frequency applications. The higher the electrical length of the liquid metal in the tube, the higher the wavelength, the lower the frequency is. A monopole of length 220mm is used to achieve radiation. The antennas characteristics such as return loss(S11 or reflection coefficient), frequency, are measured and efficiency analysed. The Proposed antenna can be used in ground based communications; radio communications, satellite communications and in vehicles such as ,on a car roof top.

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1. INTRODUCTION

1.1. Project Background

An antenna can be said to be the region of transition between a free space wave and a guided wave. [1] Its part of a transmitting system which radiates or receives energy. An antenna converts electrical current into electromagnetic waves. Any antenna whose electrical length is less than one quarter wavelength ($\frac{\lambda}{4}$) Including the ground plane is said to be an electrically short aerial.[2] The Monopole antenna was invented in 1895 by Guglielmo Marconi and has its name also being called the Marconi antenna[3].This is an antenna which is mounted vertically upon a conducting surface and is fed between the base of the antenna and the conducting ground plane[2]. A monopole antenna would radiate energy upwards towards the sky while some is radiated downwards towards the plane and outwards [2].

In the 21st century, monopole antennas are used in mobile communication systems, radio broadcasting, satellite communications and RFID. As engineers are trying to improve the performance characteristics of antennas and make tuning less complicated for devices such as cell phones which already need to link to GPS and Wi-Fi services on top of 4G and other cellular networks, and in future are likely also to have to contend millimetre-wave bands for 5G services. All those need antennas of different lengths and shapes to accommodate the sometimes widely spread wavelength bands [4]. Also reducing the weight and making designs that lead to lower costs for antennas is one of the concerns today. A liquid metal antenna that can continuously adapt to different wavelengths by changing its length inside a capillary has been made [5]. This project examines the monopole antenna and investigates how the different electrical lengths of liquid metal obtains different frequencies.

1.2. Project Aim

The main goal of this project is to design a tunable liquid metal monopole antenna which can measure different frequencies at different electrical lengths(heights) and can be used for high frequency applications. Such antenna is commonly used in the VHF (30MHz -300MHz) and UHF (300MHz – 1GHz) bands. This project would be measuring frequencies in the UHF range ; hence the length which the tube has is fit for this purpose and all the other dimensions for the test rig and the metal ground plane.

1.3. Project Objectives

This project is practical and Investigation based. The following objectives were required in order to satisfy the aim of this projects. The objectives are as follows:

- Construct measurement test rig for a liquid metal monopole antenna [6]
- Develop a pumping mechanism that can draw liquid metal up the glass tube(antenna) from a reservoir [6]
- Make a Solid plastic support with a bath (reservoir)to hold the glass tube in a steady place [6].
- Develop microcontroller hardware/software that can set the height of the liquid metal automatically [6].
- Program the stepper motor peristaltic pump to be able to regulate the liquid metal accordingly [6].
- Measure using microwave test instrument the antennas characteristic(S11) for different liquid metal heights [6].
- Evaluate the performance of the device highlighting pros/cons and consider future improvements. [6].

1.4. Project Scope

The project will mainly concentrate on studying the antennas scattering parameters , S_{11}, the power reflected from the antenna known as the reflection coefficient at different liquid metal heights in relation to the various frequencies, using a network analyser(VNA).

In this report research related to liquid metals, the manufacturing of the test rig and Pump chosen are discussed in section 2. The materials from this research were used to guide the design of this liquid metal Monopole antenna which is shown in Section 3. The measured results are shown and analysed in section 4. Section 5 evaluates the limitations in this project. In section 6, a conclusion is given and future work of this study is considered. Lastly, Section 7 appreciates and recognises all those involved in the process and contribution to the success of this work.

2. LITERATURE REVIEW

This section shows the relevant previous studies for antennas. The study has influenced the way in which the project research has been directed. The sub sections show a description of the fundamental concepts considered when modelling this antenna.

2.1. Antenna Structure

The Monopole antenna in its normal configuration is made up of a metal rod mounted vertically upon a conducting surface (ground plane) which is fed between the base of the antenna and the ground plane [2]. This is the basis for all or most monopole antennas. Although different modifications can be made to this traditional structure of this antenna such as the one in which is being considered in this project. A liquid metal antenna which takes the monopole structure is developed in this project. Also, studies in [5] shows how a liquid metal antenna which is also monopole have been tried to be developed in the past but with little success. The study also showed that NC State researchers used a voltage to control the amount of liquid metal allowed to flow into a capillary. At NC state they discovered that a voltage across the interface of a liquid metal, such as an alloy of gallium and indium(Galinstan), combined with an electrolyte could cause the liquid metal to spread or to contract, depending on whether the voltage is positive or negative. A positive voltage causes the formation of an oxide layer on the metal, lowering the surface tension and allowing it to flow easily (making it rise in the capillary), while a negative voltage removes this oxide layer, causing the metal to contract, resisting flow [5]. These liquid metal antennas could cut down on antenna farms found on planes and naval ships [5].

2.2. Liquid Metals

Liquid metals are made up of alloys with very low melting points [7]. There are several types of liquid metals namely; Gallium, indium, mercury, iron, sodium, zinc, potassium, Magnesium, caesium, and calcium. Thus, liquid metals have several properties which were looked at and were evaluated to see which is best for constructing the liquid metal antenna. Mercury used to be the standard liquid metal used, but gallium based alloys which are lower in toxicity are now used for several applications [7].

2.2.1. Liquid Metals Thermal, electrical conductivity and wetting.

Although this project doesn't focus on thermal and electrical conductivity of liquid metals, as the liquid metal in this project works based on its length, the electrical length works rises and falls depending on the air pressure. Thermal and electrical conductivity are key properties to liquid metals, so study was still found on it. Alloy systems that are liquid at room temperature have thermal conductivity far greater than ordinary non-metallic liquids [8], allowing the metal to transfer heat efficiently from the heat source to the liquid. They also have a higher electrical conductivity that allows the liquid to be pumped by more efficient, electromagnetic pumps [9]. This makes them useful for heat conducting applications such as, thermostats.

The term wetting refers to how liquid and solid interact at an interface [10]. When oxides are removed from a substrate surface most liquid metals will wet to most metallic surfaces. room-temperature liquid metal can be very reactive with certain metals. Liquid metal can dissolve most metals; however, at moderate temperatures, only some are slightly soluble, such as sodium, potassium, gold, magnesium, lead, and mercury [11]. Gallium corrodes all metals except tungsten and tantalum, which have a high resistance to corrosion. Gallium containing alloys such as Galinstan have the capability to wet surfaces which aren't metallic for example; glass.

2.2.2. Distinct Properties of liquid Metals

Liquid Metals	Appearance	Melting Point	Application	Safety	Limitations
Galinstan(Ga)	Silver [12].	−19°C[12]	• In making thermometers [13] • between heat sinks as a thermal grease [13]. • used as an efficient coolant for fission reactors [13].	Non-toxic liquid metal. Doesn't pose any serious potential threats to human health [13]. Not inflammable [13]	Wets glass surfaces, unsuitable to be used with aluminium, dissolves many metals[13].
Mercury(Hg)	Silvery white [14].	−38.87°C [14].	• filling in dentistry when it amalgams with silver [14] • Thermometers • useful in sealed electrical switches [14]	Mercury is stable (it does not react) in air and water, as well as in acids and alkalis. Toxic [15].	cause serious health problems [14].
Caesium (Cs)	Gold [16]	28.5°C[16]	• Drilling Fluid[16]. • Make special optical glass [16] • Radiation Monitoring [16]	reacts explosively in water[16]	quickly attacked by air [16].
Francium(Fr)	Silvery Grey [40]	21°C[17]	• No use due to its half-life of 22 minutes [17]	Toxic due to its radioactivity [18].	Toxic [18].
Sodium(Na)	Silvery-White[20].	97.79°C[17]	• Used as a water softener[17]. • For Heat exchanging in nuclear reactors[17].	Reacts Vigorously with water[19]. Non-Toxic, However irritates skin when it gets in contact[20].	Tarnishes when exposed to air[19].

Table 1: Properties and Comparison of Liquid Metals

After careful consideration and clear research on the following liquid metals shown above, Galinstan was chosen to be used as the liquid metal for this project. As Galinstan was already readily available as well and due to it being the safest out of all other metals, it was the best option to use. The only other alternative would have been mercury as it is non toxic as well but it poses threats to human health. As Galinstan is chosen, Below in section 2.2.3. Galinstan is further elaborated.

2.2.3. Galinstan

Galinstan is an alloy composed of gallium, indium and tin[12].It has 68.5% gallium,21.5% Indium and 10% tin[13].It is a silvery metallic liquid as said earlier, its odourless, Insoluble in water and organic solvents[13]. Galinstan is starting to be used more in medical thermometers as it is considered more accurate and much safer than traditional mercury thermometers [12]. It's proves to be a very suitable alternative to mercury.

Galinstan reacts dangerously with strong acids or oxidation agents [13]. It also wets surfaces, but to prevent the alloy wetting any substrate surface gallium oxide would be applied to coat the surface.

2.2.4. Galinstan Over Mercury

As said earlier Galinstan is not toxic and poses less threat to human health. It has a good electrical conductivity, being $3.46 \times 10^6\ s/m$ at 20℃ [12]. These properties which Galinstan possesses makes it an ideal alternative to mercury. Also disposing galinstan holds less of any environmental threats.

On the other hand, galinstan wets glass surfaces which can make it become unfit to be used as a substitute for mercury in some applications. Also it damages and dissolves many other metals[12].As mercury doesn't react in acids and alkalis[15]whereas galinstan does, it makes mercury more suitable in such applications. Also, galinstan is more expensive than mercury.

2.3. Radiation pattern of a monopole antenna

When a radio frequency current flows in a conductor a magnetic field (H) is produced around the conductor[2].The magnitude is directly proportional to the value of the current. As the current varies with time so does the strength of the Magnetic field(H)[2].The changing magnetic field produces a changing Electric field(E) in the magnetic field vicinity as well as the regions surrounding it. When the magnetic field (H) becomes constant (E) no longer exists. The direction of E depends on whether H is growing or collapsing into the antenna. A conductor carrying an RF current is always surrounded by continually changing Interdependent E & H field[2].

When an AC current is then applied in a conductor the E and H fields around the conductor will also attempt to vary sinusoidally [2]. The energy that is left outside the conductor due to the change in direction of current, and not all the magnetic field energy being returned into the conductor before the current starts to increase in direction, and as before producing new (E) and (H). This RF energy is propagated away from the conductor in the form of an EMF wave. The plane that contains the Electric field and the direction of propagation is known as polarisation of the wave.

In practice monopole antennas are used on finite sized ground planes. This affects the properties of the antenna, but in particular the radiation pattern [21].The radiation pattern results in a skewed direction[21].It radiates outwards and upwards , away from the horizontal plane .An example of radiation pattern for a Quarter-wavelength monopole antenna on a finite ground plane is shown below In figure 1(a) and (b).

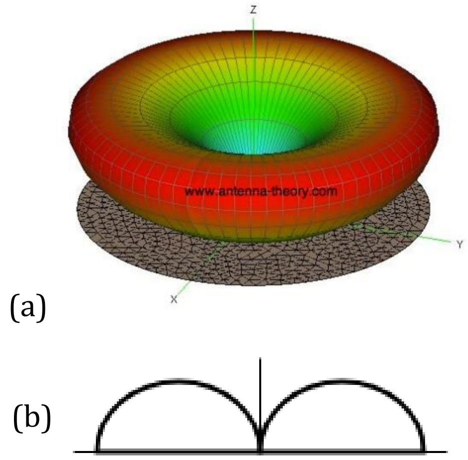


Figure 1:(a)3D- Radiation pattern for a $(\frac{\lambda}{4})$ monopole antenna on a PEC[21].(b)Radiation pattern[2].

The resulting radiation pattern for this monopole antenna is still omnidirectional [21].It still transmits signals in all directions, although the direction of peak-radiation has changed from the X-Y plane to an angle elevated from the plane[21]. The larger the ground plane is for a monopole antenna, the lower the direction of maximum radiation. As the ground plane approaches infinite size, the radiation pattern approaches a maximum in the X-Y plane.

The expression for a radiated electric field of a monopole antenna in the centre of a circular ground plane, with radius (r) is obtained using the equation below as given from[22] :

$$E = (E_0 + E_{d1} + E_{d2}).\, e_\theta \qquad (1)$$

This is the uniform geometrical theory of diffraction which has the three components for the radiated electric field of a monopole antenna in the centre of a circular ground plane.

Where: Component E_0 is the geometrical optics field of a quarter wavelength monopole

E_{d1} and E_{d2} represent the single and double diffracted field respectively for monopole height of $(\frac{\lambda}{4})$.The diagrams below in figure 2 show a monopole antenna above two ground planes

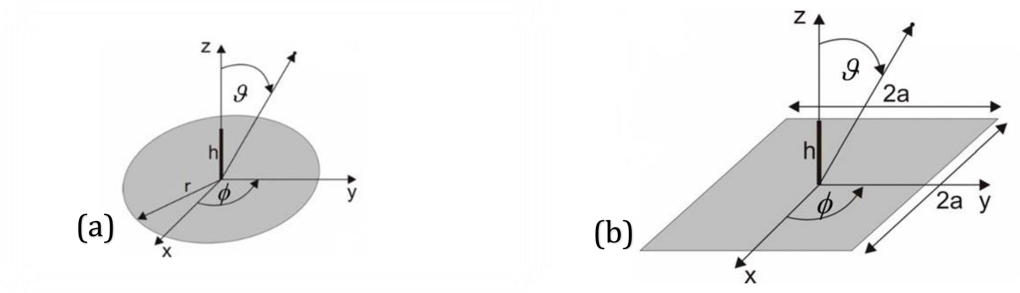


Figure 2:(a) Monopole antenna above a circular disc[22]. (b)Above a square plate[22].

Where: h represents the height if the antenna

r is radius of the circular disc or ground plane

θ zenith angle

$\emptyset$ azimuthal angle

A monopole element mounted on a ground plane of finite extent. The outer edge of the ground plane diffracts incident radiation in all directions and consequently modifies the currents on the ground plane and the vertical element from those on an infinite ground plane[23]. When the monopole element is very thin and not too long, its current distribution is approximately sinusoidal and independent of the radius of the ground plane. When the monopole element is relatively thick, its current distribution is no longer sinusoidal and its current distribution is now dependent as a function of the ground plane[23].

2.4. Matching Techniques

There are different techniques, which can be made and used to connect an antenna to a transmission line to obtain suitable frequency characteristics [24]. A number of these techniques actually depend on the structure of the antenna e.g. Micro- strip antennas are usually integrated with quarter- wave transformers [25]. A quarter wave transformer uses impedance matching , it uses a quarter wavelength piece of line of a distinct frequency with characteristic impedance Z_1. From the equation shown below as seen in [26].

$$Z_1 = \sqrt{Z_0 R_l} \tag{2}$$

Z_1 = characteristic impedance of the quarter wave line

Z_0 = characteristic impedance of input line

R_l = Input impedance of the load

Thus, when matched some of the advantages are enhancement of SNR and reduces amount of power reflected and that is wasted. Main function of this matching is to match any load impedance that's real to a transmission line.

A liquid metal antenna has to be excited to transmit or receive, and needs a feed structure which preferably is wideband, minimizes reflection and is impedance matched [27]. Another technique called the balun transforms an unbalanced source into a balanced source [27]. The word balun originated from balanced to unbalanced converter. The design can be used in RF applications such as antenna-feed networks. A microstrip transmission line can act as a balun to transform a signal from the coaxial cable(feed) to the centre of the antenna. The main principle of a balun is to solve problems of unbalanced currents , by making the magnitude of currents in feed line conductors to be equal and opposite in phase [28] .

In a nutshell, the articles and books studied in this section were broad with a lot of information. However, at the time of this research there was not to much on liquid metal reconfigurable antennas as making them integrated into electronics can be difficult. The NC state researchers are the furthest to go with this work, as they discovered that a voltage across the interface of a liquid metal, such as an alloy of gallium and indium, combined with an electrolyte could cause the liquid metal to spread or to contract[5]. Nevertheless relevant study and findings were discovered, and from this research its observed that the higher a frequency of an antenna, the higher the gain. The amount of power reflected varies depending on electrical length. Also from theory it could be calculated that the higher the electrical length of the antenna the lower the frequency which is gotten. A transferable knowledge from these papers can be used to make tunable liquid metal antennas. In recent days communication devices desire such features.

3. METHODOLOGY

The information from past studies, articles and books in section 2, has given a substantial amount of information, knowledge and understanding of the monopole antenna and also liquid metal antennas, which has enabled and helped in the development of this tunable or reconfigurable liquid metal antenna. Starting the design of this project, there where specifications which are put together shown in the table below (Table 2).

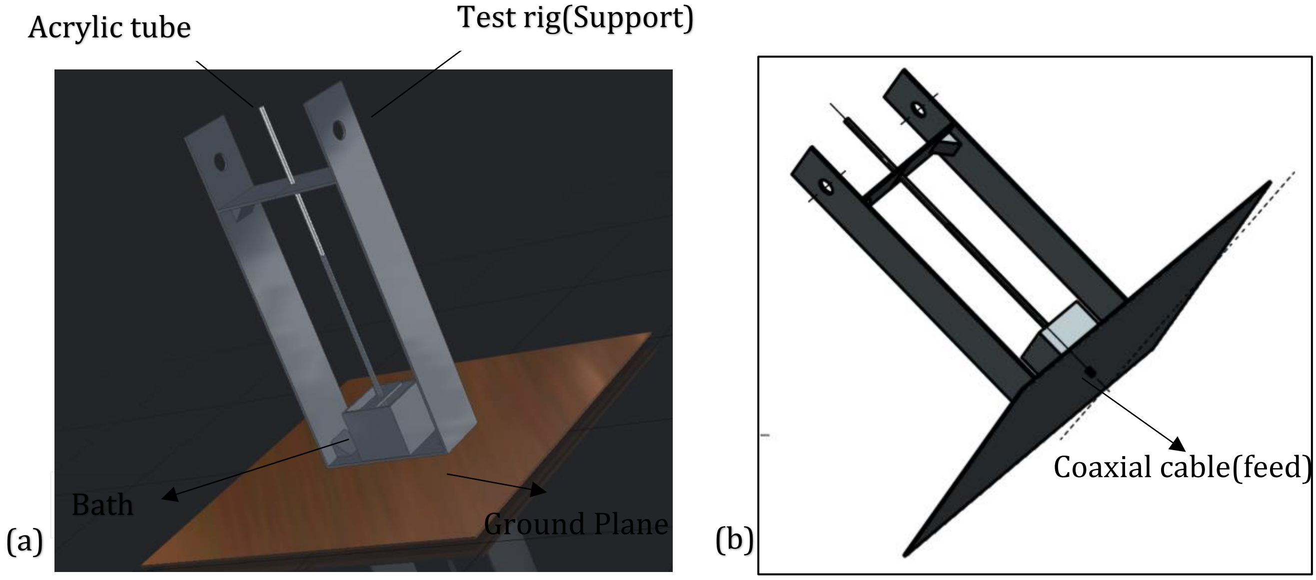
Requirements	
Structure	Monopole
Liquid Metal	Galinstan
Support (Test rig)	Solid Plastic
Bath	Solid plastic (Liquid tight)
1st Tube	Acrylic
2nd Tube	Rubber
Operating Frequency Range	UHF (340Mhz – 1Ghz)
Ground Plane	Copper (FR-4)
Pump	42 stepper motor Peristaltic pump
Microcontroller	Arduino motor shield & Arduino
Other features	Light weight, Electrically tunable.

Table 2: Antenna design specifications.

The sub sections in this methodology give a detailed explanation and justifies how the Reconfigurable liquid metal antenna has been designed. Also shows the experiments performed and the equipment used for the experiment.

3.1. Antenna Design

The whole antenna structure was drawn using computer-aided design(CAD), which enabled a lot of the manufacturing. The diagram below in figure 3 shows a 3D model of the full antenna



structure

Figure 3: (a)3-D view of the antenna. (b) Isometric 3D view

As this monopole antenna is a quarter wavelength ($\frac{\lambda}{4}$),The ground plane should be at least double the length of the antenna [29], as it gives of a better radiation. Thus the geometry shown and described in figure 4 below.

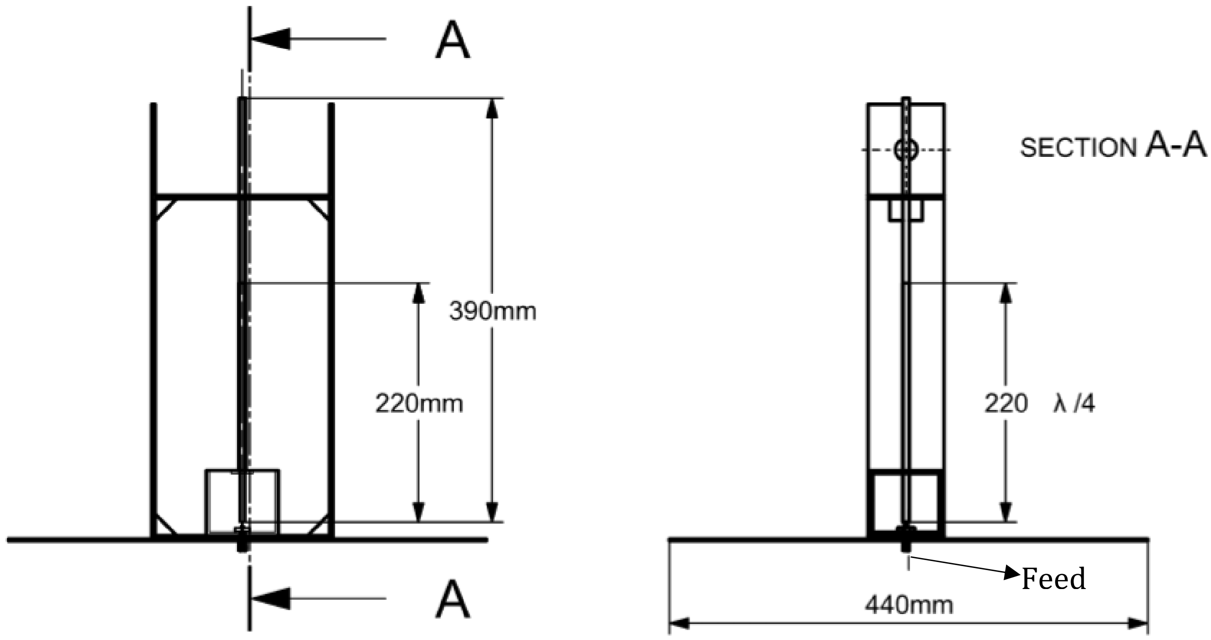


Figure 4: Geometry of the proposed antenna.

In designing this tunable antenna, Knowing the frequency range to work at was determined using the equation:

$$f = \frac{c}{\lambda} \qquad \text{Equation (3)}$$

Where: f is the frequency in hertz(Hz)

C is the speed of light (3.8×10^8)in metres per second(m/s)

λ is the wavelength in meters (m).

The highest length at which the antenna works at is 220mm (0.22m) and lowest being 75mm so from theory and calculating using equation 3 above, the highest frequency would be 1GHz and lowest being 340MHz. As this antenna is a quarter wavelength , the height of this antenna in millimetres is a quarter wavelength which means that 220mm would equals a quarter wavelength . Equation 4 shows the calculations and how the wavelength was gotten for each of this heights. Thus,

$$\frac{\lambda}{4} = L \qquad \text{Equation (4)}$$

$$\frac{\lambda}{4} = 220mm$$

$$\frac{\lambda}{4} = 0.22m, \qquad \lambda = 0.88m$$

From Equation 3: $f = \frac{3.8\times10^8}{0.88m}$ = 340MHz.

This formula showed that the higher the electrical length of the antenna the lower the frequency is. A range of different lengths where picked on the antenna which gave of different frequencies using the formula above. The range of frequencies to be tuned to and the lengths are displayed below in table 3.

Height(mm)	Height(m)	Wavelength(m)	Frequency(Hz)
220	0.22	0.88	340MHz
140	0.14	0.56	540MHz
100	0.10	0.40	750MHz
80	0.08	0.32	940MHz
75	0.075	0.30	1000MHz or 1GHz

Table 3: Range of Frequencies with lengths.

As this antenna worked with liquid metal it needed a storage for the metal which is being used to be in , this is further elaborated in the next subsection as it was part of it. Also the ground plane used was copper (FR-4) where the radiation reflects off, further talked about in sub-section 3.1.3.

3.1.1. Test Rig constructed

A Rig was constructed to be able to hold and support the antenna in place firmly. The rig had the bath for the liquid metal attached to it. That is, the whole rig included a bath. The rig had a thickness of 3mm. The bath dimensions on the rig where (60mm x 60mm) with the 3mm thickness making its width 66.5mm. The bath which is liquid tight had a section in the middle with a hole of 7mm, to hold the bottom of the antenna in place with also the top of the rig having a hole 6mm. This was decided as the tube used had an outer diameter of 6mm making it suitable to be firm in this rig. The tube was cut to 390mm, as the lowest frequency being worked at is 340MHz this would be at a height 220mm and can be gotten, as the length is more than enough. The galinstan available was 10ml, as 10 ml is a small quantity the bath dimensions where used which is more than big enough to hold the amount. The diagram in figure 5 below shows the baths geometry, its isometric and top view.

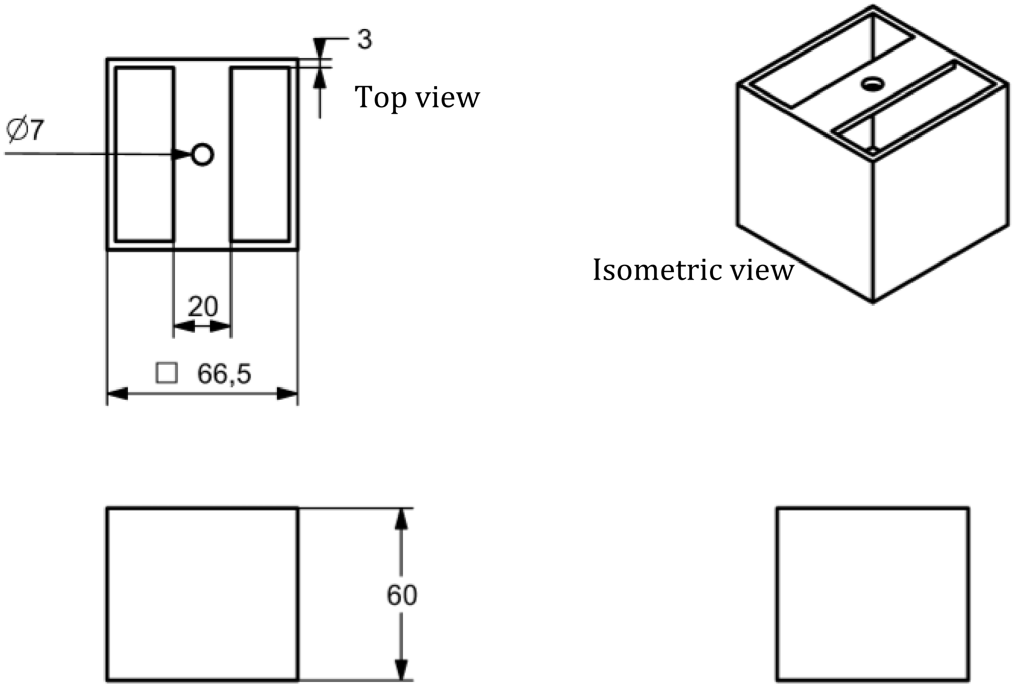


Figure 5: Bath geometry (dimensions).

The test rig made had a height of 400mm, 70mm width(breadth) and had a length of 166.4mm with the 3mm thickness. Each half of the rig was 83.2mm wide. Also this rig was made firm and to prevent it from "wobbling" using hinges also made with solid plastic, They where (20mm x20mm). Originally they were meant to be in the middle of the hinge being 30mm wide, but then was altered to extend to the whole width (70mm) of the rig. This rig also had a 20mm whole at the top to enable the rubber tube through so it could be connected to the top of the acrylic tube, as well as the pump below. The diagram below(figure 6) shows the dimensions and design of this test rig.

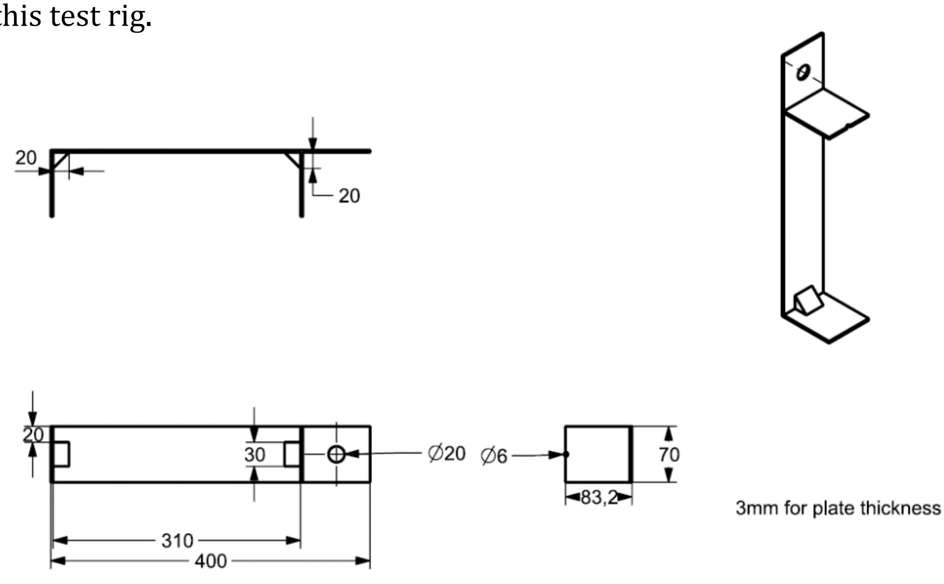


Figure: 6 Test Rig / Support design.

The full test rig assembled with the bath is shown below in Figure 7.

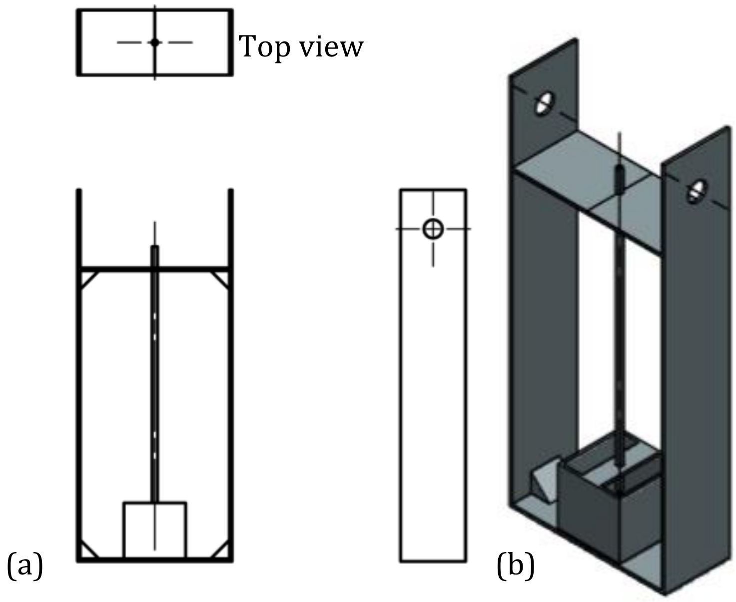


Figure 7: Test Rig (a)Front view and top view (b) isometric view

3.1.2. Pumping Mechanism

Knowing this is a reconfigurable antenna, a strategy was made in order to be able to move up and move down the liquid in the acrylic tube. A pump with a microcontroller was used to achieve this motion. The pump has one end of the rubber tube connected to it and the other end of the rubber tube to the top of the acrylic tube, as the pump reduces air pressure the liquid rises, and increases air pressure the liquid metal falls back down.

Peristaltic pump

The pump used was a 42-stepper motor peristaltic pump. The name of the pump is (42 Stepper Motor Peristaltic Pump, Dosing Pump with Tubing Hose Pump Aquarium D10). The features and details of this pump can be seen in Appendix 1. A stepper motor pump was seen as the best option to use, as the liquid can be risen in controlled steps to any given height preferred.

A stepper motor is a DC motor that rotates in precise increments. stepper motors are controlled by applying pulses of DC electricity to their internal coils, each pulse advances the motor by one step [39]. They have a magnetized geared core that is surrounded by a number of coils that act as electromagnets. There are two types of stepper motors, bipolar and unipolar. The one used in this project is a bipolar stepper motor as they generate greater torque. They have 4 wires and 2 coils, 2 wires each connected to the two coils. Controlling the currents in the electromagnets allows for stepping the motor. Applying a current to the first coil allows the rotor to be attracted to that coil and locks itself into position. When the current is taking off the first coil and applied to the second coil the rotor is attracted to that coil and that makes a Full Step Clockwise. If the voltage is then reversed the direction is reversed, as that reverses the polarity of the current. The diagram below in Figure 8 shows and gives better detail to this concept. The illustration below is shown for clarity and the step is 90degrees, in actual fact a stepper motor usually steps a fraction of this [39].

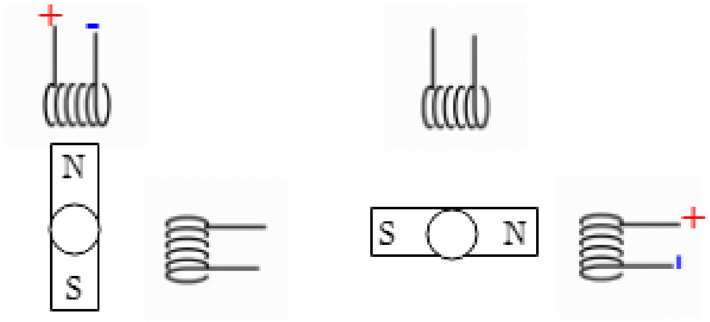


Figure 8: Stepper motor concept [39].

The first part of the diagram, the coil at the top is energized by applying electricity in the polarity shown which makes the rotor to be attracted to it and locks in place. When the electricity is then applied in the second part of the diagram to the second coil, the rotor is now attracted to that coil and locks itself in place this jump between the two positions is a full step.

The pump has a wheel or roller containing the motor, as this wheel passes along the length of the dosing tube totally compressing it, it creates suction and draws the liquid metal. The pump used in shown in figure 9.

Figure 9: 42 stepper motor peristaltic pump used.

<u>Arduino motor shield</u>

An Arduino motor shield(microcontroller) was used to control this pump, in the desired manner. An Arduino motor shield allows easy control of motor direction and speed using an Arduino, by allowing addressing of the Arduino pins.

The motor shield has 2 channels, which allows controlling of two DC motors, or 1 stepper motor. It also has 6 headers for the attachment of Tinker kit inputs, outputs, and communication lines. The use of these pins is somewhat limited [36].

There are pins on the Arduino that are always being used by the shield. By addressing these pins, you can select a motor channel to initiate, specify the motor direction (polarity), set motor speed (PWM), stop and start the motor, and monitor the current absorption of each channel [36].

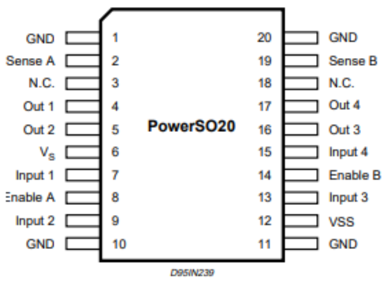
The pin breakdown as follows is shown below in Table 4:

Function	Channel A	Channel B
Direction	Digital 12	Digital 13
Speed(PWM)	Digital 3	Digital 11
Brake	Digital 9	Digital 8
Current sensing	Analog 0	Analog 1

Table 4: Pin breakdown[36].

The arduino motor shield uses motor controller L298P[35], it is based on the L298, this is a dual full bridge driver designed to drive Inductive loads such as; relays, Solenoids, DC and stepping motors[35].The L298 is an integrated monolithic circuit in a 15-lead Multiwatt and PowerSO20 packages[37].The one on this arduino motor shield comes in the powerSO20 package as it L298P.The diagram below(figure 10) shows the L298 top view of pin connections and block diagram of an L298 dual full bridge driver .

(a)



(b)

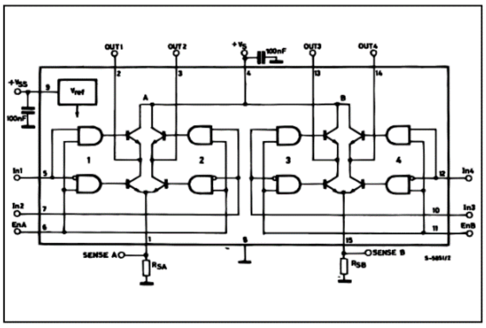


Figure 10: (a)L298P pin connections (top view) [37]. (b) Block diagram L298 Schematic [37].

The arduino motor shield also allows powering a motor with a separate power supply of up to 12v. Using an external power supply the shield was tested with the pump, as the pump wouldn't work below 3volts supplied, 9V was seen as the best power supply to use as it produced enough power for the pump to give great torque to the pump, However the power in the battery is worn out within a day. The pins of the official Arduino motor shield will only align with Arduino Uno Rev. 3. [36]. Thus that was the arduino which was used. The arduino motor shield full data sheet can be seen in Appendix 2 .

The four wires of the stepper motor which were joined to the two coils where connected to the two channels on the arduino motor shield channel A and B with the guide written on the pump. The code which is now used to make the stepper spin in both directions (clockwise and anticlockwise) in each desired step is shown in Code 1 below and explained.

```
#include <Stepper.h>

int output1 = 8;
int output2 = 9;
int enA  = 10;  // Enable pin 1 on Motor Control Shield
int enB  = 11;  // Enable pin 2 on Motor Control Shield
int dirA = 12;  // Direction pin dirA on Motor Control Shield
int dirB = 13;  // Direction pin dirB on Motor Control Shield

const int stepsPerRevolutionClockwise = 42;  // change this to fit the
number of steps per revolution for your motor

 // Initialize the stepper library on pins 8, 9, 12, 13:
Stepper myStepper(stepsPerRevolutionClockwise, output1, dirA, output2,
```

```
void setup() {
  // Set rotational speed to 60 rpm:
  myStepper.setSpeed(80);

// Enable Integrated circuit (IC3) outputs and power to the motor.
  pinMode(enA, OUTPUT);
  digitalWrite (enA, HIGH);
  pinMode(enB, OUTPUT);
  digitalWrite (enB, HIGH);
}

void loop() {
  // Step 42 times for one revolution into one direction:
  myStepper.step(-stepsPerRevolutionClockwise*42); //rises liquid  ----------
------220mm
  delay(3000);// wait 3 seconds before continuing 20 steps anticlockwise to
220mm

   // Step 20 revolution into one direction:
  myStepper.step(-stepsPerRevolutionClockwise*20); //rises liquid  ----------
------continue to 220mm
  delay(20000); // wait 20 seconds before going clockwise, drop to next step
record on NA

   //  Step 14 times one revolution in the other direction:
  myStepper.step(stepsPerRevolutionClockwise*14); //drops the liquid  -------
--------140mm
  delay(20000);  // wait 20 seconds before going clockwise again

  //  Step 8 times in one revolution in the other direction:
  myStepper.step(stepsPerRevolutionClockwise*8); //drops the liquid  --------
-------100mm
  delay(20000);   // wait 20 seconds before going clockwise again

  //  Step 6 times in one revolution in the other direction:
  myStepper.step(stepsPerRevolutionClockwise*6); //drops the liquid  --------
-------80mm
  delay(20000);   // wait 20 seconds before going clockwise again

   //  Step twice in one revolution in the other direction:
  myStepper.step(stepsPerRevolutionClockwise*2); //drops the liquid  --------
-------75mm
  delay(20000);   // wait 20 seconds before going clockwise again
}
```

Code 1: Stepper motor pump [38]

The program shown above drives a bipolar stepper motor. The motor should revolve one revolution anticlockwise which rises the liquid according to the amount of steps given, then revolves in the other direction with the according steps to drop to each desired length and record the frequency on the Network analyser.

The stepper library which was included is gotten from the arduino IDE and its used for this program. First thing that was done were the pin definitions. Pin 12 and 13 defined for the two channel directions, 8 and 9 as the 2 outputs , and enable channel A on pin 10 and B on pin 11.

The function “steps per revolution” defines the number of steps in one revolution of the motor. The steps per revolution for the motor used was defined as a constant integer of 42 and can be changed depending on the amount of steps available for a motor. As the pins have been defined they were initialized on the stepper library using the stepper function which creates an instance of the stepper class called "mystepper" which represents the stepper motor connected to the arduino board. The pins used are 8,9,12 and 13.

When the "mystepper()" is called the function "setspeed()" sets the motor speed in rotations per minute(Rpm). The ouputs of the IC (L298P) are enabled and powers the motor, as enA and enB the two channels, are set to HIGH.

The step function in the loop, turns the motor the specific number of steps wanted both clockwise and anticlockwise.

The diagram of the arduino motor shield with the 9V power supply connected to the 42 stepping peristaltic pump is shown below(Figure 11):

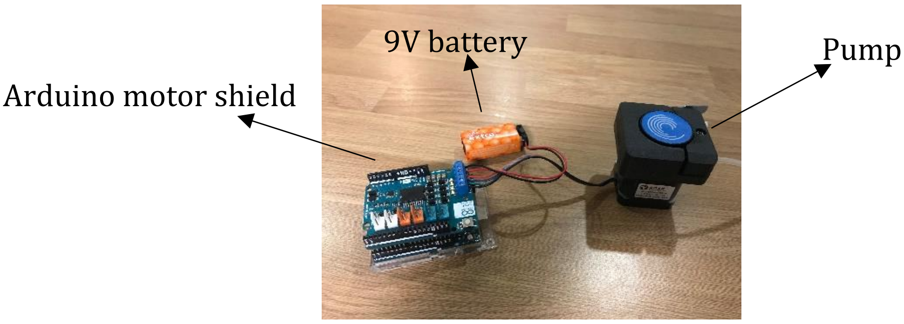


Figure 11: Arduino motor shield connected to the Peristaltic pump.

3.1.3. Ground plane

In building this tunable antenna which takes the monopole structure, it requires a ground plane. The ground plane reflects radio waves and it should be conductive. The conducting plane used must extend for at least a quarter wavelength from base of the antenna as said earlier. The ground plane used was made of copper (FR-4) which has a dielectric of 4.8[33]. Although it wasn't a double-sided sheet with copper, only one side the top which would be conductive. As this plane must extend for at least a quarter wave length of the antenna, the ground plane was made to be double the length of the antenna which was (220mm), it also had a 7mm whole in the middle to fit the feed (RF connector) which was 6mm in diameter and had a thickness of 1.4mm. Thus, the designed diagram is shown below in figure 12 with the dimensions used and the 3D model. Following the designs and the dimensions the actual manufactured ground plane is shown in Figure 13.

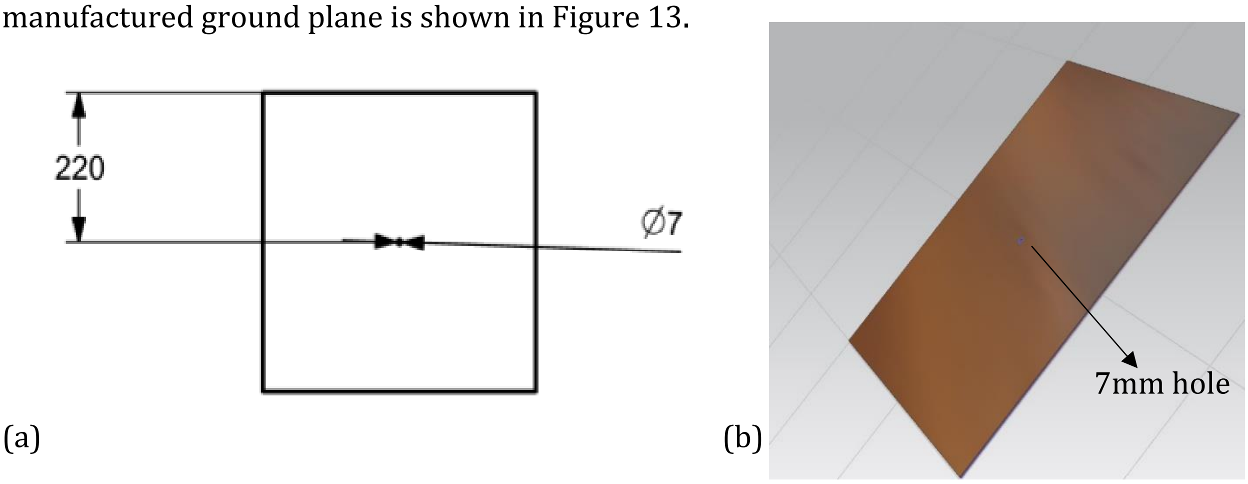


Figure 12: (a). Ground plane Geometry (b)3D View

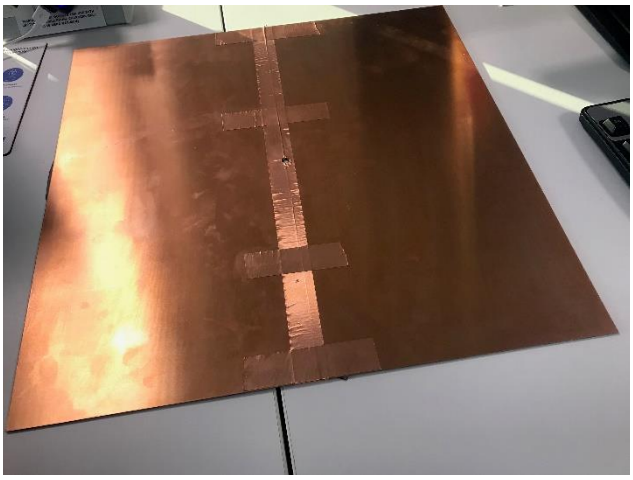


Figure 13: Actual ground plane manufactured and used.

3.1.4. Feeding Technique

Feeding is the way an antenna would be connected to a receiver or transmitter. This antenna was fed using a coax feeder (radio frequency connector). A 50Ω panel mount subminiature version A connector was used. It had a PTFE(polytetrafluoroethylene) dielectric which is 2.1 [33]. A coax feeder has a central conductor usually made of copper, a dielectric spacing, an outer conductor also (copper) and an outer protective sheath. The inner conductor touches the liquid metal, which is also conductive. As the liquid is stored in the bath and the coax feeder is also in the bath which goes all the way through, meaning its outer and inner conductor are both in the bath and then its screwed under the ground plane, this is mechanically right, but electrically wouldn't be because it would cause short circuiting, which means it would have low electrical impedance and low radiation. This was now seen as mechanically correct but not electrically correct, So as part of the design to prevent this happening and to make it electrically correct the outer conductor was covered with an acetate sheet as it pierced the central conductor and sat on the dielectric. The galinstan would also be above as it's on the sheet and the sheet was above the outer conductor. This outer conductor was also covered with polythene and Blue tack made of Bingham plastic to prevent any contact of the liquid metal at all with the outer conductor. Figure 14 below shows a skeletal view of the bath with the RF connector (coax feeder).

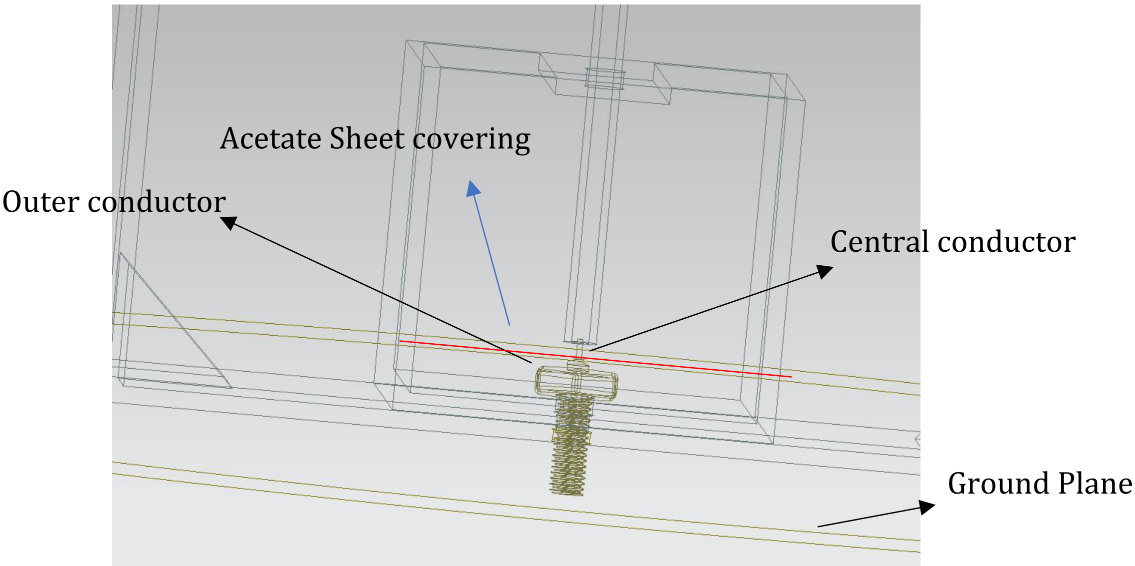


Figure 14: Skeletal view of bath with RF connector and Ground plane.

After completing this antenna design, the procedure for experimenting was undertaken which is shown in the next section.

3.2. Experimental Procedure

The experimental procedure involved, using a (VNA) Vector network analyser connected with a microwave cable to the antenna (load). The Anritsu 37397D VNA was used in this project to measure, the S11 and some characteristic impedance. As antenna measurements are verified and validated with antenna theory, the results gotten from the VNA at different electrical lengths where compared to the results calculated and expected for this antenna.

This experiment was carried out using a syringe to pull up the liquid metal to different desired heights in the acrylic tube, as using the pump in conjunction with a power supply would've crowded the work space. Also as a property of galinstan is wetting, the tube used got wet after pulling up the liquid a couple of times and made it harder to look at the lengths measured on the tube. So to make the experiment and measurements more accurate five different tubes where used and marked with the five different heights and where changed each time to get the almost accurate frequency on the VNA.

The five different acrylic tubes with the marks, used are shown below in fig 15:

Figure 15: Five tubes marked with different Heights.

This experimental procedure first showed an unexpected result. As this project involves pouring the galinstan into the bath with the acetate sheet and then drawing up the liquid metal to different heights to get the various frequencies expected, an important observation was noted. Drawing up the liquid metal the results did not change and the VNA only gave off one frequency being 1.79GHz which is shown in Figure 16. It was then noted that the antenna first worked as a patch antenna. The bath of the test rig for this antenna was quite big as to actually contain a lot of liquid metal which made the antenna act as a successful patch antenna before it was gotten into a monopole. A patch antenna consists of a patch of metal(shaped metal) mounted over a larger sheet of metal(ground plane) with a dielectric in between and it gives off one high frequency. A patch antenna having the "patch" of metal length to be half a wavelength. This was calculated in theory to see if it did actually act as one. The width of the bath is 60mm so the galinstan put in was shaped in a square and was distributed into 60mm. using the equation showed below this verified that it acted as a patch antenna at first.

$\frac{\lambda}{2} = 60mm$ Equation (5)

$$f = c\lambda = 120mm$$

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8}{0.120} = 2.5GHz$$

Further explaining the patch response, as the antenna behaved as a patch , the dielectric of the plastic used is 3. The ABS solid plastic having this dielectric meant that , both air spacing and the plastic acted as a dielectric. Thus, the average frequency was gotten. Following the equation below:

$\frac{C}{\sqrt{E_r}}$ Equation(6)

This equation was used to get the speed of light in ABS, this is further solved below,

$$\frac{3 \times 10^8}{\sqrt{3}} = 1.7 \times 10^8 m/s$$

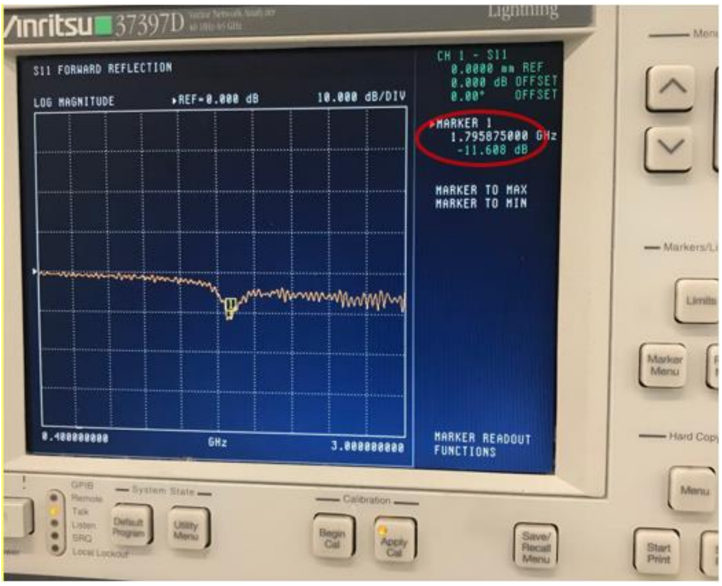
Thus, $f = \frac{C}{\lambda\sqrt{E_r}} = \frac{3\times10^8}{0.120 \times\sqrt{3}} = 1.4GHz$

The frequency gotten due to the ABS plastic is 1.4GHz and then in air its 2.5GHz. Hence, this means as a patch antenna it would give off a frequency not lower than 1.4GHz and not higher than 2.5GHz. The average was solved to get the middle frequency:

$$\frac{1.4 + 2.5}{2} = 1.95GHz$$

This is not at all far from the 1.8GHz frequency shown below on the VNA in figure 16.

The diagrams below in (Figure 16) shows the displayed results from the VNA, verifying this calculation is right:

(a) 

(b) 

Figure 16:(a) VNA results showing antenna acting as patch(b) The amount of liquid metal which made it act as a patch.

During this procedure to make this antenna behave in the expected way, it was then made sure that at all times of measurements there was little or no liquid metal left in the bath when measuring and also the amount of liquid metal put in the bath, was just right to all be drawn up in the tube to the desired height, so that there will be no liquid metal or negligible amount left in the bath. This was achieved by trial and error. However it was determined that in future work to make this reconfigurable monopole antenna only behave as a monopole and not a patch, the bath used should have a smaller size.

The full antenna build for the experimental procedure is shown in fig 17 below:

Figure 17: Antenna build for the experimental procedure.

Example of the antenna measurements are shown below in figure 18, at the lowest length measured 75mm and highest length measured 220mm:

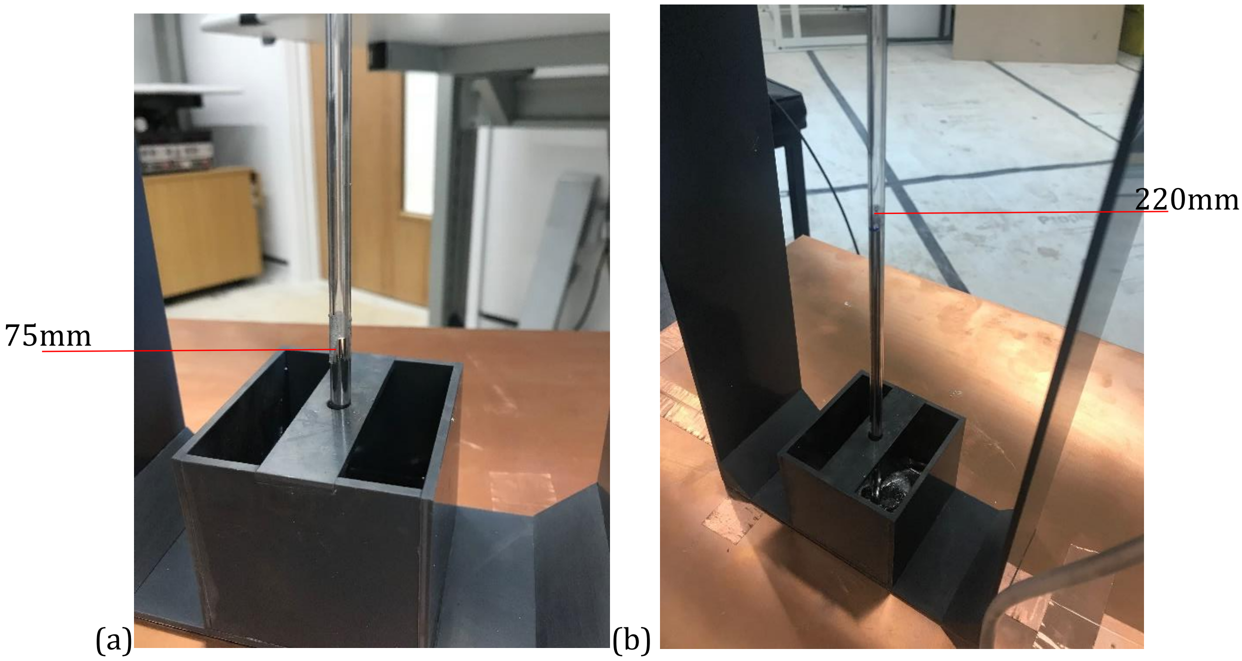


Figure 18:(a) electrical length of antenna at 75mm.(b) Electrical length of antenna at 220mm

3.2.1. Measurement from Test bench

The Anritsu 37397D VNA was the equipment used for the test bench measurement and is shown in Figure 19.

Figure 19: Experimental set-up on the bench

Before these measurements were carried out , the VNA is first calibrated using the Anritsu calibration tool kit(K connector calibration kit 3652 series) in order to reduce the errors gotten from the experiment as well as achieve the best possible result. The calibration tool kit contains all the precision components for calibration the VNA, supporting calibration with open , short and broadband loads. Beginning this calibration, instructions are followed on the VNA , the open is connected to the port 1 and then connected to port 2, then the short is connected to both as well. The open is now connected to the port 2 and the short connected to the port 1. Following that the two ports are connected to each other.

When this calibration has been done, the VNAs validity Is verified by adding a matched load of 50ohm connected to each ports end and its seen that it has a very low return loss at -80dB. It also showed that the characteristic impedance measured was 49.450Ω -218.585jmΩ. The test showed what can be expected when a 50Ω RF connector(Z_s) is connected to a load(Z_l) having a characteristic impedance and is in agreement. A completely straight line is shown on the screen of the VNA before connecting this antenna.

4. RESULTS AND DISCUSSION

The numerical and graphical representation of the antenna's performance in S_{11} terms, are presented and discussed in this section. The theoretical calculations for the electrical lengths are compared to the actual VNA measurements at the different electrical lengths. The results show that by tuning this antenna to the different lengths the resonant frequencies are varied. The five figures below show the diagrammatic representation of the VNAs result of the measured lengths.M1 in this result, indicates the frequency gotten at the measured heights on the VNA and M2 is the expected frequency from the theoretical calculations for the different heights. The results gotten from the VNA are copied on a floppy disk and are then analysed on a computer using the National Instruments AWR design environment.

4.1. Parametric Analysis

The study of the effective different heights of the monopole antenna and the effects on the S_{11} is taking into account, the optimised antenna lengths were identified with the S_{11} responses.

4.1.1. Effective Heights of the monopole antenna

The frequencies gotten with the electrical lengths are shown below from figure 20- figure 24:

75mm

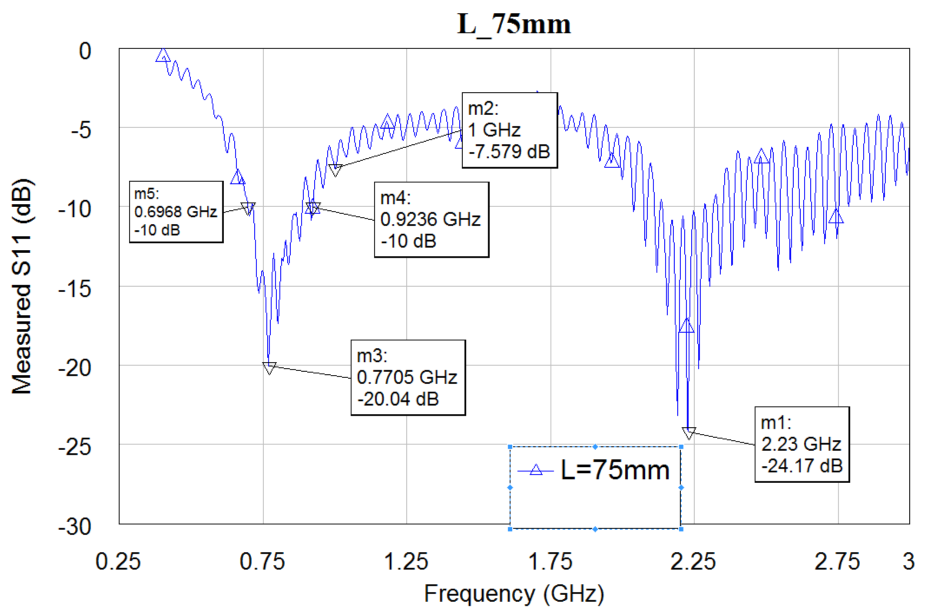


Figure 20: Antennas performance in terms of S_{11} at electrical length 75mm.

From the graph above it can be said that this antenna works best at 770MHz or 0.77GHz. As that is the first resonance which is the fundamental and principle frequency, it can be seen that the peak is deep and it shown that it has a low return loss, this entails that there is less power being reflected back from the antenna and more power being absorbed, which also tells most of the EM wave goes through the load. The reflection coefficient here is low and that's desirable, desirably the $S_{(1,1)}$ should be below the -10 dB value which is shown here and makes the antenna efficient. The second resonance here which is the 3rd harmonic, shows it also has a low return loss and its frequency is 2.23GHz, at this frequency it can be said that the antenna would also work best.

In this particular graph the M3 which is 0.77GHz is the results gotten from the VNA for this height and M2 which is 1GHz is the expected result of frequency from the theoretical calculation. Its seen that the results of theory are not at all far off from the VNAs results. Looking at the -10dB bandwidth, frequencies at which the returned loss values is below(-10dB) is of the range 0.7 GHz to 0.9 GHz. This means the bandwidth has a gap of about

200MHz, 227MHz to be precise or 0.23GHz in which this antenna can safely work. The greater the bandwidth the more efficient the antenna is as it shows more accommodation.

80mm

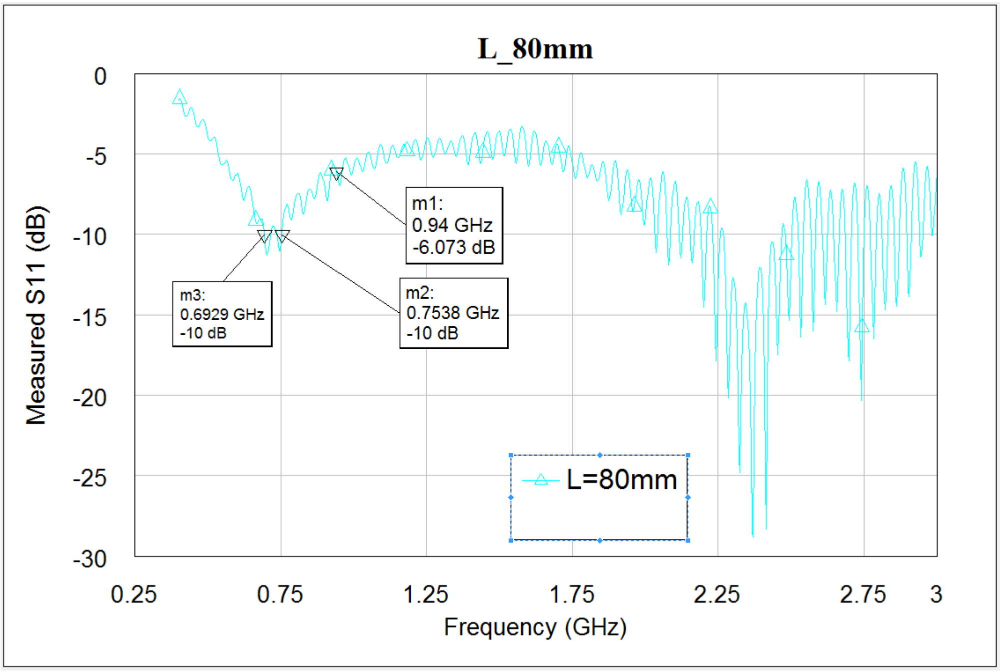


Figure 21: Antennas performance in terms of S_{11} at electrical length 80mm.

From this results in figure 21 there's a poor reflection co-efficient and this is due to not being enough power delivered to the antenna. More power is being reflected and it gives a reflection coefficient of -10 dB. The measured frequency at this height gotten on the VNA is 0.75GHz or 754 MHz at m2, and m1 is marked showing where the expected frequency(0.94GHz or 940Mhz) at this height is meant to be, the results are also not far off from each other and are also really close. The bandwidth gap at this 80mm height is very low as well. This shows the antenna at this height inefficient or doesn't work very well.

100mm

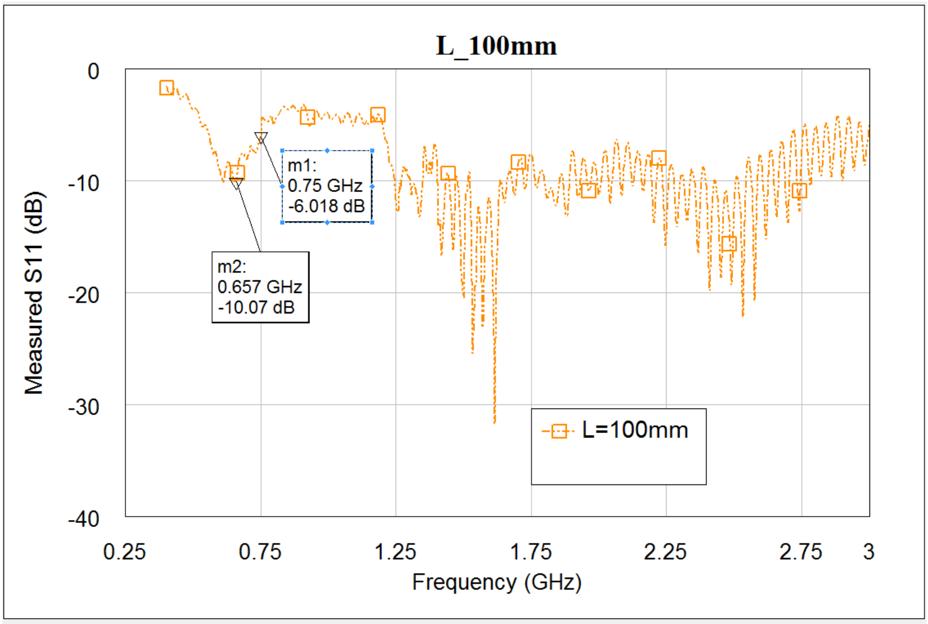


Figure 22: Antennas performance in terms of S_{11} at electrical length 100mm.

The 100mm height also shows that the reflection coefficient here is poor and also that less power is being taken into the load(Antenna). The peak isn't deep. With the VNA giving a measure of 0.66GHz or 657MHz marked with m2 and m1 marks the expected height from theory which is 0.75 GHz or 750MHz. The results measured are very close to the theory when compared. M2(0.66GHz) shows a reflection coefficient of-6 dB while the expected frequency 0.75GHz gives a return loss of -6 dB. Thus, the return loss of the measured frequency is actually lower than that of the expected frequency. From the graph looking at -10 dB, the bandwidth at which this antenna can safely work is seen also to be very low.

140mm

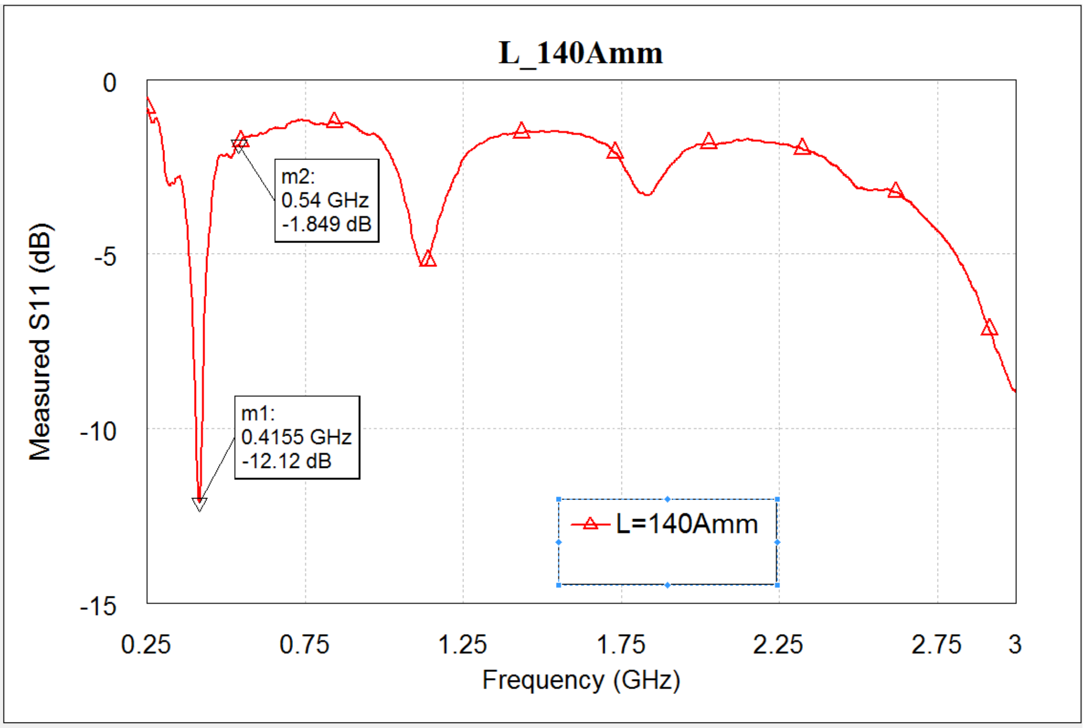


Figure 23: Antennas performance in terms of S_{11} at electrical length 140mm.

The 140mm electrical length shows the measured frequency from the VNA is 0.42GHz or 415MHz. At this frequency the reflection coefficient here is very low and also below – 10 dB, which is desirable. However, it can be seen that the bandwidth at -10 dB is very narrow or very small, which means the gap of bandwidth which this antenna can safely work at this height is very low and so is less efficient to accommodate. For example if walkie talkies are sold to customers, and the frequency at which a customer is working at is not to interfere with the others, different frequencies can be assigned within the bandwidth. Thus, a smaller bandwidth means less amount of customers could be assigned or work over various frequencies within that bandwidth.

The expected frequency at this height which is marked at m2 is 0.54GHz or 540MHz is also not far from the measured frequency at m1 being 0.42GHz or 415MHz .This graph also shows three resonances.

220mm

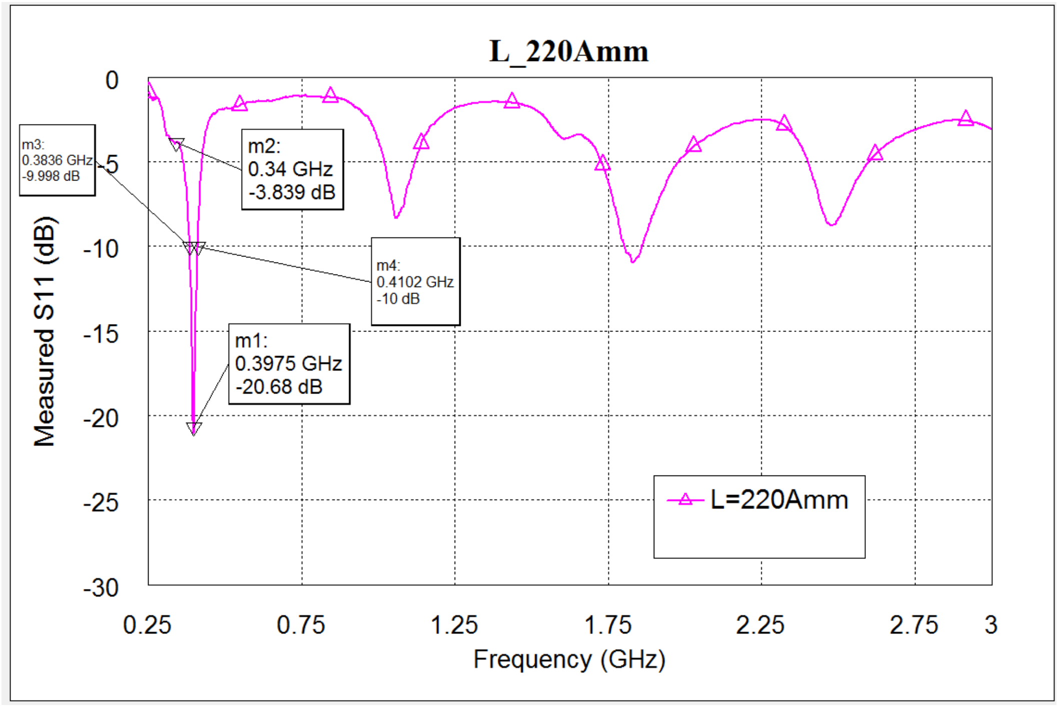


Figure 24: Antennas performance in terms of S_{11} at electrical length 220mm.

Theoretically this height was calculated to give a frequency of 340MHz or 0.34GHz,but the measured frequency gotten was 397MHz or 0.40GHz. This is close giving a 57MHz gap between the two. The return loss here is very low , at 397MHz giving -20.68 dB. However, the bandwidth is very narrow, Looking at -10 dB. The bandwidth gap at -10dB, is 30MHz or 0.03GHz , this means the range of frequencies at which this antenna can properly radiate when looked at the principle resonance is very low.

To further explain return loss, it was analysed with matching. A smith chart was taken for the characteristic impedance of two heights which is shown in Appendix 3 and Appendix 4. Its seen in Appendix 3 that in terms of match the second resonance at 75mm is better as it gives a return loss of 0,although it has a lower bandwidth than the first. The reflection coefficient is said to be 0 , based on looking at the characteristic impedance. The diagram in Appendix 3 shows that the characteristic impedance at 2.23GHz which is 50Ω matches, as the impedance from the port $Z_s = Z_l$, using the equation of reflection coefficient shown below:

$$\Gamma = \frac{Z_S - Z_l}{Z_S + Z_l} \qquad (7)$$

Z_S is the characteristic impedance of port S_{11}

Z_l is the characteristic impedance of the load(antenna in this case).

When reflection coefficient is 0, the whole EM wave goes through the load. The characteristic impedance at 2.23 GHz “matches” better than the characteristic impedance of the principle frequency (0.77GHz).Thus, at 0.77GHz the characteristic impedance is less but not far off being 43Ω hence it still has less power being reflected and is the fundamental resonance.

Looking at Appendix 4 for the 80mm smith chart, the impedance was 27Ω at 0.75GHz .This is a mismatch and hence in figure 21 it can be seen that the reflection coefficient is great , as this characteristic impedance of the load is far from the characteristic impedance of the port.

Concluding these results, it can be said that all the measured frequencies from the VNA are slightly lower than theory apart from the 220mm electrical length. The theoretical electrical length is shorter compared to the length of the fabricated sample and the EM wave sees a longer length than the one designed in the model. Also its noticed that the first three electrical lengths that were measured (75mm,80mm, and 100mm) have ripples which shows that noise was given off in those signals and the later (140mm and 220mm) has no noise present. This was due to the fact that when the first three lengths where measured the VNA was only calibrated to the port and the 300mm length of microwave cable wasn't calibrated ,this made the length of cable act as part of the antenna. The length of cable was then calibrated using the same procedure for calibrating the VNA and this then made the results more accurate and visible as they were less ripples.

Table 5 below shows all the measured results from the VNA and the expected results:

Height(mm)	Height(m)	Wavelength(m)	Expected theoretical Frequency(Hz)	VNA measured frequency(Hz)
220	0.22	0.88	340MHz	397MHz
140	0.14	0.56	540MHz	415MHz
100	0.10	0.40	750MHz	657MHz
80	0.08	0.32	940MHz	754MHZ
75	0.075	0.30	1000MHz or 1GHz	770MHz or 0.77GHz

Table 5: Frequency results from theory and Vector network analyser

Figure 25 below shows all the electrical lengths together below.

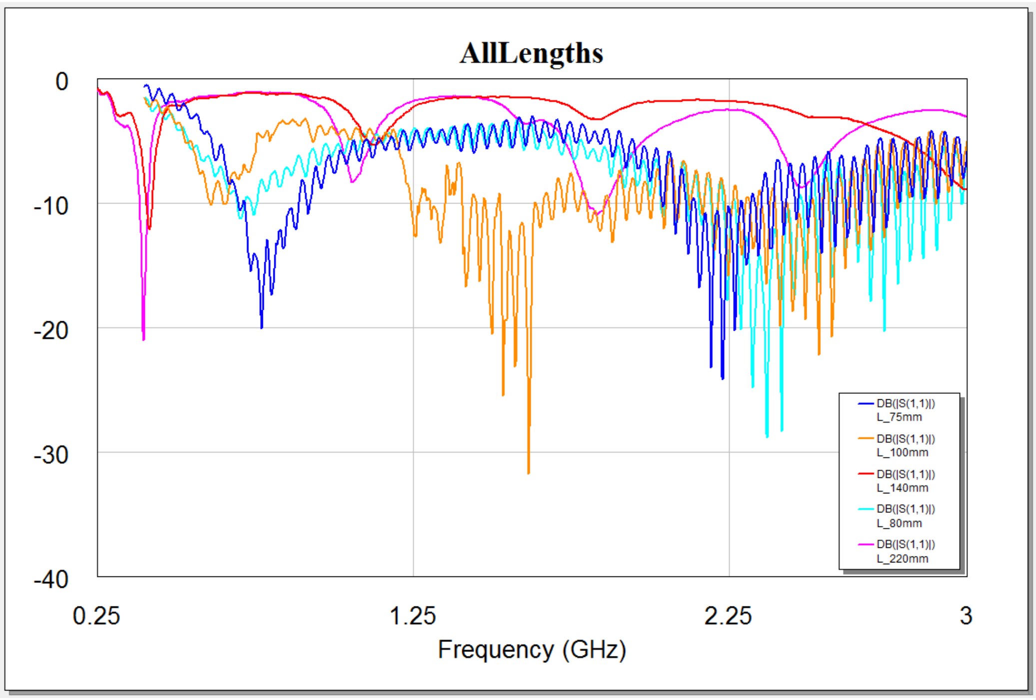


Figure 25:Variations of the S_{11} of the liquid metal(monopole antenna) at different electrical lengths shown together

The results displayed above in section four showing that the measured frequencies from the VNA are slightly lower than theory excluding 220mm electrical length. The variation could be as a result of the dielectric of galinstan which is between(1.24 - 3.1).[31]

5. LIMITATIONS

There were some limitations which where gotten during the course of undergoing this project. Firstly, As galinstan wetting properties where not fully considered and seen as subtle, so not too much time was allocated into taking that factor. This limited the sight of the individual seeing the measurement on the tube. Also galinstan being an electrical conductive metal , during the experiment it was noticed that if the liquid metal was moved up past the desired length of the tube when measuring, then due to its conductivity the recorded frequency on the VNA would be where it stopped at first regardless of taking it lower to the desired length, so it had to be taken newly, on a new tube or patiently wait for the liquid metal to drop from the mistaken height and remeasure.

Secondly, Due to the viscosity of galinstan which is (0.0024Pa-s) at room temperature, it takes longer to draw it up, although it could still be drawn up. A liquid metal with lower viscosity, which is also non-toxic should be considered.

6. CONCLUSION AND FUTURE WORK

In this report, a prototype and very optimistic reconfigurable liquid metal (monopole antenna), fed by a 50Ω Radio frequency connector subminiature version A, has been developed and presented. The antenna operates in the Ultra high frequency range, tuning to frequency between 340MHz-1GHz. Good agreements between the theoretical and measured results has been observed, as its seen that the higher the effective electrical length of the antenna the lower the frequency which would be measured. From most of the results achieved on the VNA, 60% of the tunable heights gave off a well desired reflection coefficient, only two of which gave poor reflection coefficient. As antennas desire to achieve the lowest return loss possible, the obtained results satisfy the specifications required for antenna satellite communications. This antenna can also be considered as two antennas in one, due to the fact that a patch response would be received if too much liquid metal is put into the bath making it act as a patch antenna. The aims and objectives of this project can be seen to be fulfilled as well.

In most practical or observational projects there will be chances for improvements and better results, which can also be applied in the case of this project. Areas that can be considered for future work include:

- Prevention of galinstan wetting – As galinstans wetting properties where not properly considered in this project, once galinstan is risen to a particular height in the tube, taking it to a lower marked height is harder to see in the tube, to prevent this more research should be considered into using gallium oxide to coat the tube and prevent wetting, so the marked heights are more visible.
- Using a calibrated tube- the different heights on the acrylic tube used were measured with a metre rule of up to 300mm and marked with permanent marker, It would be more accurate to use a calibrated tube with a scale, this would produce better results.

- Bath size and Acetate sheet- Further investigation should be taken into reducing the bath size, so it would act only as a monopole and not a patch antenna. The larger bath size took more galinstan on the acetate sheet which made it act as a metal sheet over another metal ground plane at first. A smaller bath size would mean the amount of galinstan would be reduced ,neglible and might be just the amount required to make it just a monopole. Also as the bath design had the region for the tubes support connected to it, it made just a slight complication with getting the RF connector through. Making this easier, the region for the tube can be made as attachable and detachable so the RF connector can be easier to put through. An example of detachable support is shown below in Appendix 5.
- Patch response- The patch response received is acknowledged and further research should be looked into considering the antenna as a possible design for a patch antenna.
- Using conducting Radials – The ground plane for this antenna was $440 \times 440mm$ having half of its length to be quarter wave-length, it was balanced on two stools, making it able to connect the microwave cable and also it was quite expensive to make. Investigation should be looked into considering four conducting quarter wavelength radials [32]. This would provide a sufficient simulation of the complete ground plane.
- Presence of an anechoic chamber -The use of an anechoic chamber makes the experiment more controlled than just the test bench measurement. Using this chamber would further improve the results as there is no interference from the outer world, due to the anechoic chamber room being covered with pyramidal electromagnetic wave absorbing materials which minimises reflections.

7. ACKNOWLEDGEMENTS

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APPENDICES

[Appendix 1]

Speed Range	1 – 50rpm (reversible)
Velocity resolution	0.1rpm
Power Consumption	Less than 10W
Stepper Motor	42 stepper motor
Pump head Weight	80g
Motor weight	400g
Protection class	IP31
Flow rate range	0-160ml/min

Table 6: Peristaltic pump technical details[30].

[Appendix 2]

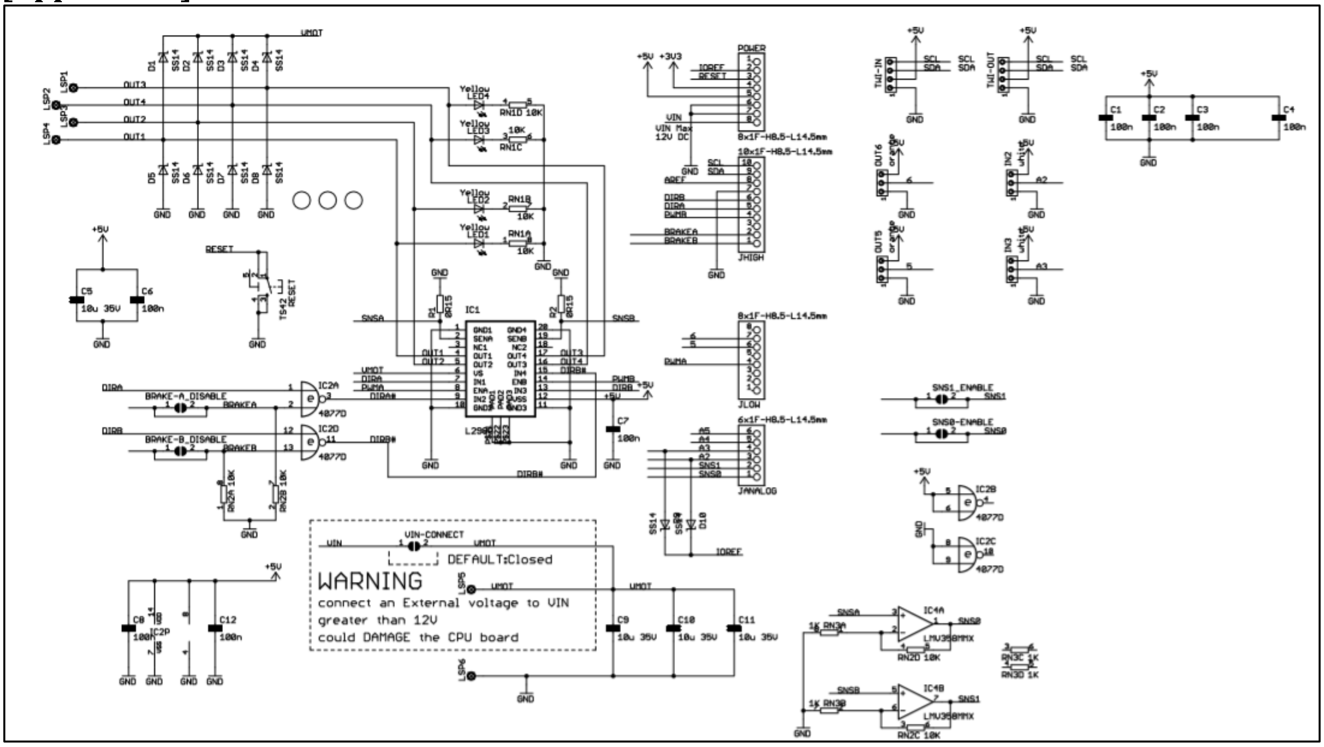

Figure 26: Arduino Motor shield datasheet[34]

[Appendix 3]

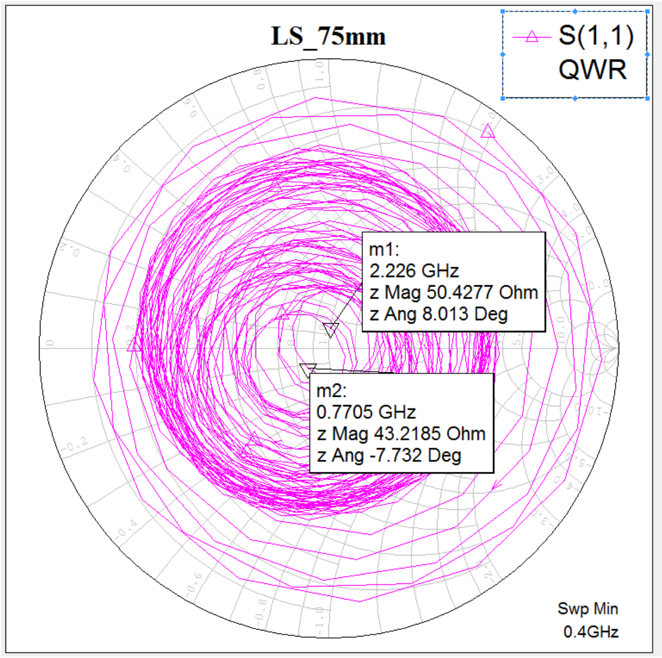

Figure 27: Smith chart showing characteristic impedance at 75mm

[Appendix 4]

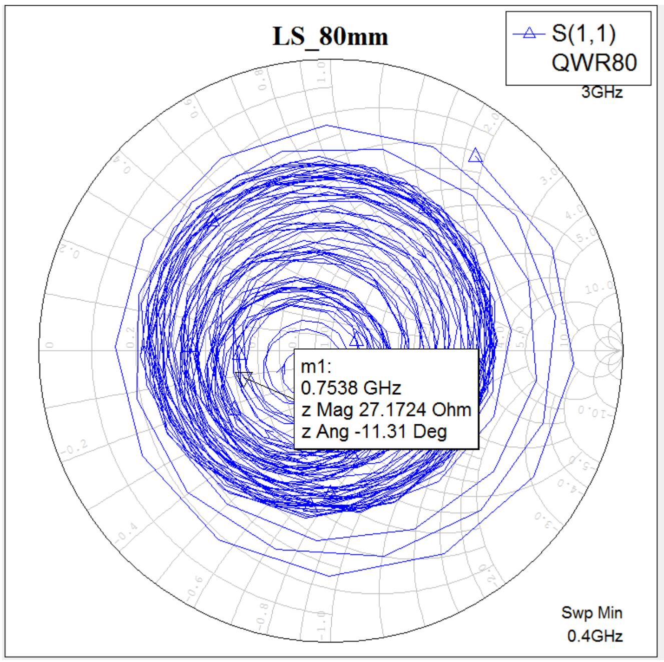

Figure 28: Smith chart showing characteristic impedance at 80mm

[Appendix 5]

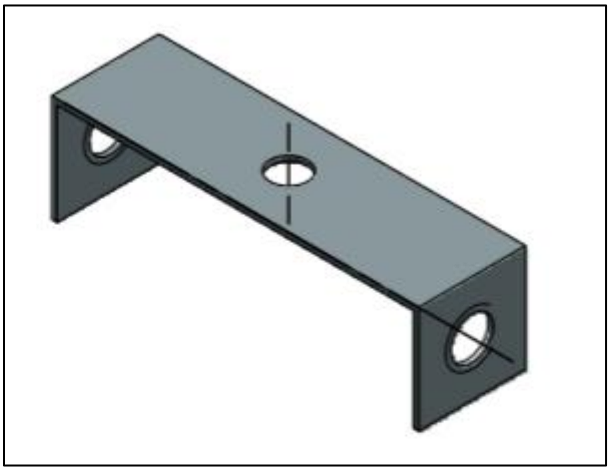

Figure 29: Example of detachable tube support for the bath.

[Appendix 6]

Figure 30: Full antenna build