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Liquid Metal Reconfigurable Antenna System

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I. Introduction

1. Rapid advancements in wireless communication technologies, driven by innovations like 6G, Internet of Things (IoT), Satellite communication, EW Systems and wearable sensors, have created a surge in demand for antennas with high adaptability and operational efficiency. These next-generation technologies require communication systems capable of handling diverse and complex scenarios, such as supporting multiband operations, ensuring seamless connectivity across various devices, and managing the challenges of high-data rates as well as low-latency. At the core of these systems lie antennas, the essential components accountable for transmitting as well as receiving electromagnetic signals.
2. Conventional antennas, widely used for decades, are typically designed for fixed frequency bands and operate with a predetermined set of characteristics. While effective in traditional communication setups, they fall short in catering to the dynamic requirements of modern wireless technologies. Their static nature prevents them from adjusting to the varying frequency and operational demands of multiband systems. For instance, a conventional antenna used in a single-band application cannot be easily repurposed for a different frequency without physical modifications or entirely replacing the design. This limitation underscores the growing need for antennas that are versatile, adaptive, and capable of reconfiguring their properties in real-time.
3. Reconfigurable antennas have stood out as a promising solution to this challenge. Unlike conventional designs, these antennas are capable of altering their operating parameters, encompassing radiation pattern, frequency, or polarization, for meeting demands of different applications. The flexibility of reconfigurable antennas can be achieved by utilising multiple mechanisms, such as electronic switches, material changes, or mechanical adjustments. For example, frequency reconfiguration can be achieved using components like PIN diodes or varactors, which enable tuning across multiple bands by altering the antenna's electrical properties. Similarly, beam steering and pattern reconfiguration can be achieved through techniques like phase shifting or physical repositioning of antenna elements.
4. Among the innovative approaches to reconfigurable antenna design, liquid metal-based antennas represent ground-breaking advancement. Liquid metals, such as Galinstan, offer unique properties that make them highly suitable for reconfigurable applications. These materials are conductive, malleable, and capable of dynamically reshaping within a given structure, such as a micro-fluidic channel. This allows for seamless adjustments to antenna's geometry and, consequently, its operational characteristics. Integration of liquid metals in antenna design has opened up new possibilities for achieving continuous tunability, wide bandwidth, and high efficiency.
5. In conclusion, demands of modern wireless technologies necessitate a shift from traditional antenna designs to reconfigurable solutions. By offering adaptability, multiband operation, and enhanced performance, reconfigurable antennas, especially those utilizing liquid metal technology, are going to achieve a pivotal role in upgrading the future of wireless communication. Their ability to dynamically respond to changing operational needs ensures they remain a cornerstone of innovation in this rapidly evolving field.

Motivation towards Liquid Metal Reconfigurable Antennas

6. This study is motivated by the associated drawbacks of traditional reconfigurable antenna approaches as well as current developments in micro-fluidics and their uses in military applications. This can be summed up as follows:

(a) Evaluation of viability of liquid metals in reconfigurable antenna applications along with limitations of conventional reconfiguration techniques by presenting various study cases.
(b) The Evaluation of overall RF performance which isn't possible by employing traditional techniques (frequency tuning, frequency bandwidth, pattern applications).
(c) Comparison of performance of liquid metal with commonly used methods, in various antenna types like patch antenna and Yagi-Uda antenna.

7. Mercury a well-known metal that is liquid at room temperature has found its utility in this field, Galinstan, alloy of gallium, indium, and tin. The combination of high conductivity, low viscosity, and reconfigurability allows liquid metals to offer significant advantages in antenna technology, particularly in applications requiring dynamic adjustments, such as frequency tuning, beam steering, and polarization changes.

S.No	Property	Mercury	Galistan	eGaln
(a)	Material Composition	Hg	"Galliun-68.5% Indium-21.5% Tin Or Stannum- 10%	Galliun-75.5% Indium-24.5%
(b)	Appearance at room temp	Liquid	Liquid"	Liquid
(c)	Melting point (degree C)	-38.83	-19	15.5
(d)	Boiling point (degree C)	356.7	>1300	2000
(e)	Viscosity(Pa.s)	1.55x 10(3)	2.4 x 10(-3)	2.0 x 10(-3)
(f)	Density(Kg/m3) @ 20 degree C	13600	"6440	6280
(g)	Surface Tension(N/m)	0.465	0.718	0.624
(h)	Electrical Conductivity(S/m)"	1.02 x 10(6)	3.46 x 10(6)	3.4 x 10(6)
(j)	Thermal conductivity (W/m.K)	8.50	16.5	26.4

Table 1-1: Materials used in Liquid Metal Antennas.

8. Essential characteristic of liquid metals is their **high conductivity**. This property is crucial for antenna systems, as it directly influences efficiency of signal transmission. In traditional antennas, materials like copper or aluminium are used due to their high conductivity. However, liquid metals, such as Galinstan, offer similar or even superior conductivity in some cases, with the added benefit of being adaptable in real-time.
9. Another critical property of liquid metals is their **low viscosity**. Viscosity refers to resistance a fluid offers in flow, and in case of liquid metals, the low viscosity allows them to flow easily within micro-fluidic channels or other confined spaces. This property is useful in reconfigurable antenna designs, where liquid metal can be injected, removed, or redistributed within the antenna structure. The ability to manipulate the liquid metal flow provides precise control over antenna's geometry as well as operational characteristics. With liquid metals, antennas can change their physical form on demand, allowing continuous adaptation to the environment or operational conditions.
10. In addition to frequency tuning, liquid metal antennas can facilitate **beam steering and polarization adjustments**. Beam steering refers to the capability in which antenna's radiation pattern is changed, while polarization adjustments allow for altering the orientation of the electromagnetic waves. These capabilities are critical in advanced communication systems that require adaptive beamforming and high-performance signal propagation in dynamic environments.

Research Objectives

11. Design liquid metal reconfigurable antennas using HFSS.
12. Evaluate their performance, including return loss, gain, and bandwidth.
13. Address challenges in integrating liquid metal antennas with existing RF systems.

Scope and Structure of the Dissertation

14. This dissertation presents a comprehensive study on liquid metal antennas, focusing on their potential as reconfigurable components in modern wireless communication systems. The research explores unique characteristics of liquid metals, such as conductivity (high), low viscosity, and reconfigurability, which make them ideal candidates for dynamic antenna designs.
15. The literature review in *Chapter 2* delves into existing reconfigurable antenna technologies, highlighting the challenges and limitations of traditional designs. It also discusses the advantages of liquid metal antennas, such as their ability to achieve frequency tuning, beam steering, and polarization adjustments, essential for emerging technologies like 5G and IoT.

16. In *Chapter 3*, the dissertation outlines the methodology used to design, simulate, and optimize liquid metal antennas. High-Frequency Structure Simulator (HFSS) is employed for modelling the electromagnetic behaviour of the antennas, and the simulation process is explained in detail. This chapter also covers the material properties of Galinstan and the integration of microfluidic channels for antenna reconfiguration.
17. *Chapter 4* provides results and discussion of the simulations, providing an evaluation of antenna's performance. It includes metrics like bandwidth, return loss, gain, and radiation patterns. Findings highlight significant improvements in performance compared to traditional fixed-frequency 2-antennas, demonstrating the advantages of liquid metal reconfigurability.
18. Chapter 5 concludes dissertation by providing key findings, limitations, along with future research directions for further enhancing practical applications of liquid metal antennas in wireless communication systems.

II. Literature Review

Antenna Fundamentals

1. The performance of any antenna can be characterized on basis of few parameters encompassing Return Loss, Bandwidth, VSWR, Radiation Pattern, Polarization, Radiation Efficiency as well as Gain. Detailed explanation of fundamental antenna parameters with equations and diagrams has been provided below:

Radiation Pattern

2. **Radiation pattern** of antenna is graphical representation of radiated electromagnetic waves in various directions. It describes how power is distributed in space when antenna transmits or receives signals.
3. **Types of Radiation Patterns**

(a) **Omni-directional Pattern–** Radiates equally in all directions in a particular plane (e.g., dipole antenna).
(b) **Directional Pattern –** Focuses energy in a specific direction (e.g., Yagi-Uda, horn antennas).
(c) **Isotropic Pattern –** A theoretical antenna that radiates equally in all directions (ideal reference).

4. **Key Components**

(a) **Main Lobe:** The primary direction in which the antenna radiates the most energy.
(b) **Side Lobes**: Unwanted radiation in other directions is usually minimized to reduce interference.
(c) **Back Lobe:** Radiation in the opposite direction of the main lobe is ideally minimized.
(d) **Nulls:** Directions where radiation is nearly zero.

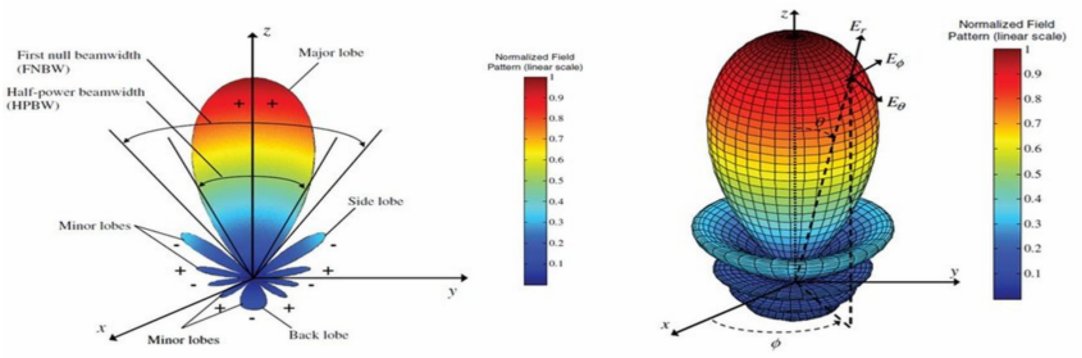


Fig 2-1: Normalized 3D Far-Field Pattern

Field Regions

5. Space around antenna is split into distinct regions on basis of distance from antenna in addition to behaviour of electromagnetic fields. These regions help in understanding radiation properties and are classified into 3 main zones:

a) Far-Field Region (Fraunhofer Region)
b) Radiating Near-Field Region (Fresnel Region)
c) Reactive Near-Field Region (Fresnel Region)

6. Out of which Fraunhofer region is radiative region where angular distribution of power remains constant. Hence for antenna measurements, communication and radar applications Far-field region is the prominent one. Far-field region can be considered "by equation as,

Here, r = Distance from antenna, D = Larger dimension of the antenna, and λ = Wavelength in free space".

Gain and Directivity

7. **Directivity (D)** is the measure of how concentrated the radiation is to that of isotropic radiator directionally.
8. **Gain (G)** is directivity multiplied by efficiency (η), considering losses.

Where, U_{max} = Maximum Radiation Intensity, U_{avg} = Average Radiation Intensity,
P_{rad} = Radiated Power and η = Radiation Efficiency.

Antenna Polarization

9. **Polarization** of antenna corresponds to orientation of **electric field (E-field)** of radiated electromagnetic wave. It is an essential parameter in antenna design because **mismatched polarization between transmitting and receiving antennas results in signal loss**. Polarization can be broadly classified into 3 types,

a) Circular Polarization
b) Elliptical Polarization
c) Linear Polarization

10. **Cross-Polarization & Polarization Mismatch**

(a) **Cross-Polarization** is when the transmitted and received polarizations are orthogonal, causing signal degradation.
(b) **Polarization Loss Factor (PLF**) measures signal loss because of polarization mismatch:

Where, θ is the angle between the transmitting and receiving polarization planes.

Return Loss and VSWR

11. **Return Loss (RL)** and **Voltage Standing Wave Ratio (VSWR)** are parameters employed for evaluating impedance matching of an antenna with its feed line. Proper impedance matching assures **maximum power transfer** in addition to **minimal signal reflection**.
12**. Return Loss** estimates amount of power being **reflected** back through antenna because of impedance mismatch. It is represented in **decibels (dB)**, where a **higher negative value** suggests better "matching.

Where Γ =Reflection Coefficient and it's provided by,

Where, Z_L=Load Impedance (Antenna Impedance), Z_0=Characteristic Impedance of the Transmission Line (usually 50Ω)

VSWR is a ratio of **maximum voltage** to **minimum voltage** in standing wave pattern" alongside transmission line. It represents how efficiently power is transmitted without reflections.

Bandwidth

13. **Bandwidth** represents range of frequencies over which an antenna can work efficiently while maintaining acceptable performance concerning impedance matching, gain, and radiation characteristics. It is expressed in **Hertz (Hz)** or as **percentage of the centre frequency**.

Here, f_H and $f_L$are upper and lower cut-off frequencies, and f_C is centre frequency.

Theory of Microstrip Patch Antenna

14. **Patch Antenna and its design**

(a) A **Microstrip patch antenna (MPA)** is a lightweight and planar antenna widely used in wireless communication, radar, and satellite applications. It consists of dielectric substrate which has radiating patch on one side, and ground plane on other. Patch which contains conductive material like copper or gold, is designed in various shapes (rectangular, circular, or other geometries) to achieve desired performance. MPAs operate based on **fringing fields** and are commonly excited using Microstrip lines, coaxial probes, or aperture coupling techniques. They offer advantages like ease of fabrication, integration with RF circuits, and conformability to surfaces, but suffer from narrow bandwidth and low gain, which can be improved through advanced design techniques such as array configurations, stacked patches, and defected ground structures.
(b) The design of Patch is to achieve its pattern maximum, normal to patch (broadside radiator). Mode (field configuration) of excitation is deciding factor in this(includes End Fire Radiation). For rectangular patch,

length L of element is $\lambda_0/3<L<\lambda_0/2$. There is dielectric (substrate) separating strip (patch) along with ground plane, as shown in Figure 2-2.

(c) There are multiple options for choosing substrates used for designing Microstrip antennas with dielectric constants in range of $2.2\leq \varepsilon_r\leq 12$(mostly). A good dielectric has thick substrate with dielectric constant in lower end of range as it offers larger bandwidth, better efficiency, loosely bound fields for radiation into space, however, size is large. Thin substrates exhibiting higher dielectric constants are most favoured in microwave setup as the requirement of tightly bound fields (minimising undesired radiation as well as coupling) is eminent in these.

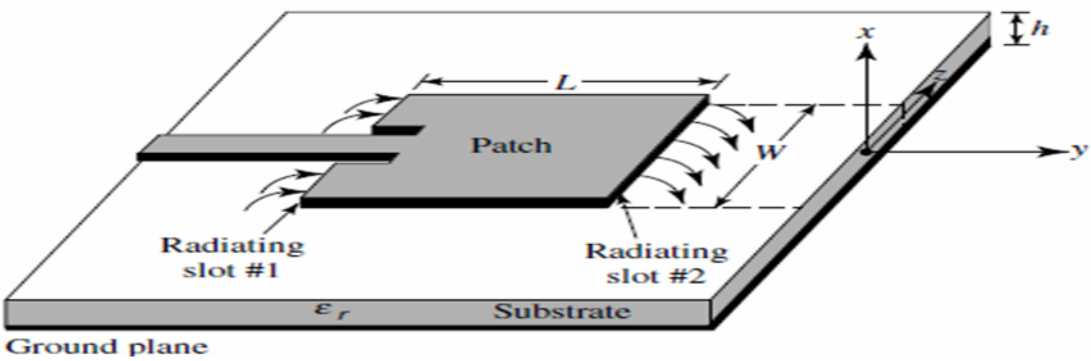


Fig 2-2: 3D View of Microstrip Patch Antenna

(d) Designing a Microstrip patch antenna requires various key parameters to determine its dimensions, performance, and operating characteristics.

i. Operating Frequency (f_r)
ii. Dielectric Substrate Properties
iii. Substrate Thickness (h)
iv. Relative Permittivity (ε_r)
v. Loss Tangent ($\tan\delta$)

(e) Patch Antenna Dimensions

(i) Patch Width (W)

$$W = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r+1}{2}}}$$

Here, c=Speed of Light (

(ii) Effective Dielectric Constant (ε_{eff})

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{-0.5}$$

(iii) Effective Length (L_{eff})

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}}$$

(iv) Length Extension (Correction)

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(W/h+0.264)}{(\varepsilon_{eff}-0.258)(W/h+0.8)}$$

(v) Patch Length (L)

$$L = L_{eff} - 2\Delta L$$

(vi) Ground Length

$$L_g = 6h + L, \quad W_g = 6h + W$$

15. **Yagi Uda Antenna**

(a) Yagi-Uda antenna, a staple in radio frequency technology, presents substantial advancement in realm of antenna design, primarily due to its unique directional capabilities. Originally developed in the 1920s, this type of antenna utilizes an array of elements, including driven elements, reflectors, along with directors, to effectively improve signal reception as well as transmission. The precise arrangement of these components allows for increased gain and a more focused beamwidth, which is particularly advantageous in applications requiring long-distance communication.

(b) Structure and Components of Yagi Uda Antenna. Central to operation of Yagi Uda antenna is its distinct structure, typically comprises several key components: reflector, driven element, along with one or more directors. Driven element, usually dipole, is responsible for receiving as well as transmitting radio signals, while the reflector serves to direct these signals forward, enhancing gain and overall performance. Directors, placed in front of driven element, enhance directivity by focusing the emitted signals in a specific direction. This arrangement permits Yagi Uda antenna for exhibiting high gain in addition to selective reception capabilities, which can significantly improve connectivity, particularly in areas plagued by weak signals

(c) Structure of Yagi Uda antenna. Yagi Uda antenna can be divided into the following elements

(i) Driven Elements. This is an active element of the antenna connected to the supply. Based on the operability, it can be Dipole or Folded dipole in most Yagi antenna

(ii) Reflector elements. These are the elements that are not connected to the supply. These are used to reflect the back lobe of driven element.

(iii) Director Elements. These are antenna's elements that are passive ie these are not connected to the supply. These are used to direct the Major lobe of the driven elements.

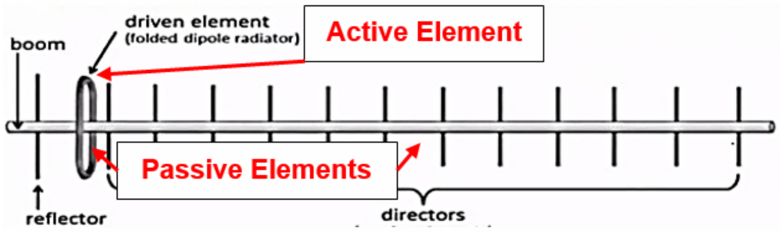


Fig 2-3: Structure of Yagi-Uda antenna

(d) Radiation of Yagi Uda Antenna.

(i) Principle. if impedance mismatch is being utilised between radiator (driven element) and reflector (passive element). Back lobe created by the folded dipole is being completely reflected by the reflector element thus resulting in enlarging the front lobe. Similarly, the directors (passive elements) are being used to further direct and increase the size of the front lobe. As the number of directors increases, the size of the lobe keeps increasing.

(ii) The figure below illustrates the process: -

(aa) At first, the folded dipole is driven, it forms front and back lobes

(ab) In the second step, when a reflector is placed with complete impedance mismatch, this causes the back lobe to be reflected leaving only small back lobes.

(ac) Directors are being placed to direct or increase directivity in front lobe.

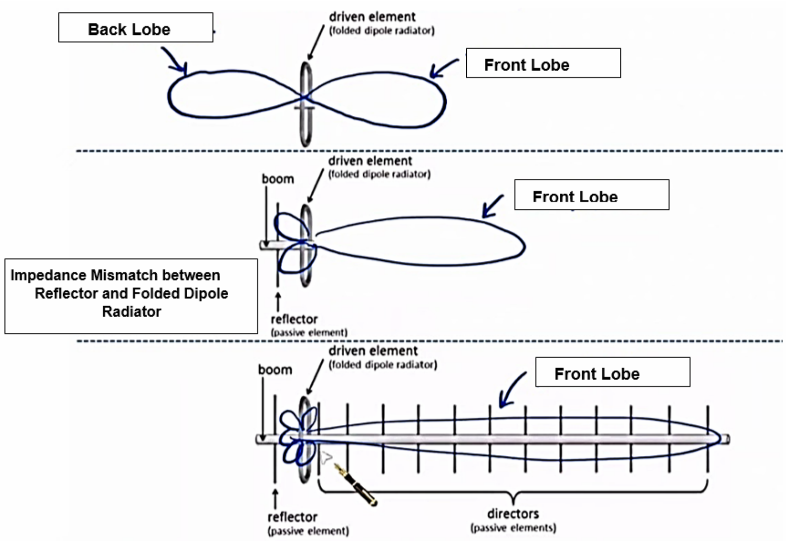
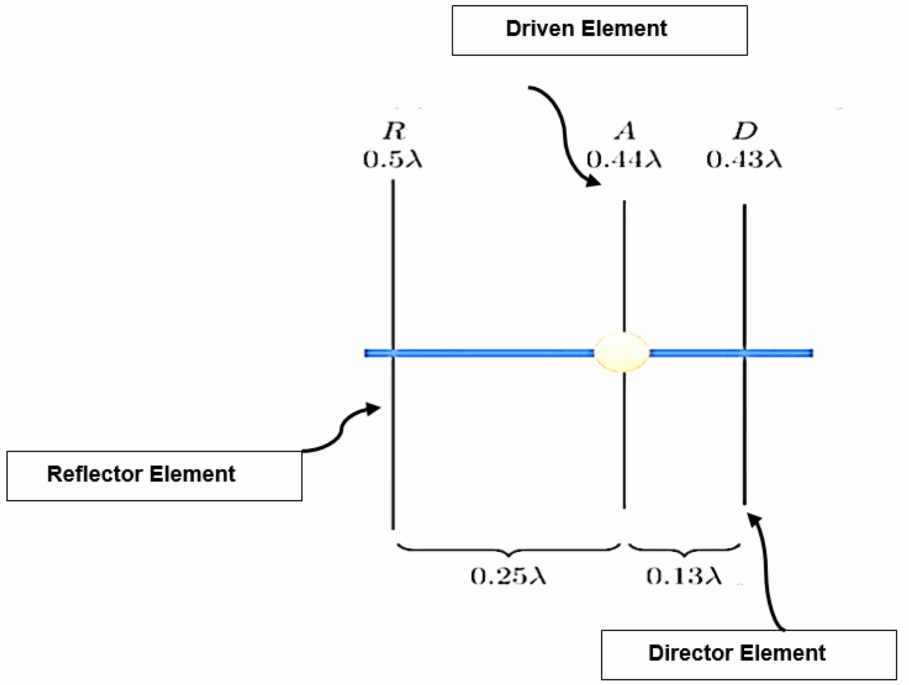


Fig 2-4: Principle of Yagi-Uda Antenna

Designing of three-element Yagi Uda Antenna.



Fif 2-5: Three Element Yagi-Uda Antenna

Basic parameters for designing are as follows: -

Table 2-1: Three Element Yagi-Uda Antenna

ELEMENT	SPECIFICATION
Length of the Driven Element	0.458 to 0.5
Length of the Reflector	0.55 to 0.58
Length of the Director 1	0.45
Length of the Director 2	0.40
Length of the Director 3	0.35

(g) **Feeding Mechanism**

(i) The **feed mechanism** is responsible for transferring RF power to Microstrip patch antenna for radiation. Selection of feeding technique depends on **impedance matching, polarization, and bandwidth requirements**.

(ii) **Coaxial Probe Feed (Pin Feed) -** Determines **feed point location** based on input impedance.

(iii) **Microstrip Line Feed -** Requires characteristic impedance matching (50Ω).

(iv) **Aperture Coupled/ Proximity Coupled Feed-** Improves bandwidth performance.

(v) Out-of-which Microstrip Line feed is most prominent and easiest one to handle and we are also going to use the Line feed in our design.

(h) Despite their advantages, Microstrip patch antennas (MPAs) have several limitations:

(i) Narrow Bandwidth

(aa) Typically 2-5% of the operating frequency.

(ab) Limits applications requiring wideband or multiband operation.

(ac) Can be improved using stacked patches, aperture coupling, or slot-loading techniques.

(ii) Surface Wave Losses

(aa) Energy is partially trapped within the substrate, reducing radiation efficiency.

(ab) Increases unwanted coupling in antenna arrays.

(ac) Can be minimized using low-dielectric constant substrates.

(j) Though there are few more demerits with MPA's the above ones are the prominent ones which made us move to Reconfigurable antennas. Reconfigurable antennas had advantage of increasing Bandwidth, multi-band configuration, Polarization tuning and so on. In the upcoming review, we are going to discuss generic reconfigurability (electrical) techniques from the Literature.

Reconfigurable Antennas

16. Reconfigurable antennas are substantial advancement in antenna technology, offering dynamic adjustments to their operational characteristics, encompassing radiation pattern, frequency, as well as polarization. These antennas can adapt to varying communication needs, enabling more efficient spectrum use and improving system performance. The reconfiguration is typically achieved through several mechanisms, including electronic switches, material property changes, and physical modifications to the antenna structure. Each of these methods permits real time antenna tuning, offering the flexibility necessary for meeting demands of modern wireless communication systems.
17. Electronic switches, such as PIN diodes or varactors, are commonly employed in reconfigurable antennas to adjust the frequency or radiation pattern. By varying the impedance or capacitance in response to an electrical signal, these devices can alter antenna's resonance frequency or direction of radiation beam. Another method involves changing the material characteristics of antenna, encompassing altering dielectric constant of substrate or conductivity of material through external stimuli like voltage or temperature. This allows for on-the-fly adjustments to the antenna's characteristics. A more straightforward approach for achieving reconfigurability is through physical modifications, where the geometry of the antenna is altered by mechanical means. This includes methods like folding, extending, or reshaping the antenna, which can alter its electrical properties like resonant frequency or polarization. There are lots of reconfigurable techniques which are broadly discussed in below Table 2-1.

Techniques	**Components Used**	**Control Mechanism**
Electronic Switching	PIN Diodes, Varactors	DC biasing
MEMS-Based Switching	Micro-electro mechanical systems	Electrostatic Actuation
Optical Tuning	Photoconductive materials	Optical illumination
Material-based tuning	Liquid Metal, Graphene	Thermal or electrical bias
Mechanical Tuning	Moving Parts, Stretchable antennas	Actuators or deformation

Table 2-2: Reconfigurable Techniques

18. While these techniques have proven effective in certain applications, liquid metal antennas offer a distinct advantage by enabling seamless geometric reconfiguration. Liquid metals, such as Galinstan, possess unique characteristics that make them ideal for this purpose. Galinstan, for instance, is a non-toxic, highly conductive liquid that remains in liquid state at room temperature. Ability of liquid metals to flow and change shape within a controlled environment—such as micro-fluidic channels—makes them highly suitable for reconfigurable antenna systems. These antennas can dynamically alter their geometry, such as length, width, or shape, to optimize their performance, enabling frequency tuning, beam steering, and polarization adjustments without the need for mechanical switches or external power sources. By adjusting the volume or distribution of liquid metal within a micro-fluidic channel, the antenna's resonant frequency can be tuned over wide range, allowing for multiband operation. Similarly, by manipulating the liquid metal's shape, the radiation pattern can be steered, and polarization can be modified, providing significant benefits in dynamic wireless communication environments.
19. Another key benefit of liquid metal antennas is their robustness and adaptability. These antennas can maintain high performance even in the presence of external forces such as mechanical deformation or environmental changes, making them ideal for use in harsh or variable conditions. Moreover, liquid metal antennas are well-suited for integration with other advanced technologies, such as flexible electronics and wearable devices, due to their inherent reconfigurability and adaptability to various form factors.

Liquid Reconfigurable Metal Antennas

20. **Liquid Metal, liquid metal Alloys and their Characteristics.** Mercury and Galinstan have emerged as a highly promising material in various technological fields, especially in realm of reconfigurable antenna design. Fwg are the most noticeable properties: -

(a) **Low melting point**

(i) One of the most notable characteristics is the ability of remaining in liquid state at room temperature. Unlike many other metals, which require high temperatures to become liquid, Mercury and Galinstan's low melting point make then uniquely suitable for applications where a fluidic metal is required for dynamic manipulation and reconfiguration.

(ii) This property is particularly advantageous in the development of liquid metal antennas, as it offers range of benefits that traditional solid-material antennas cannot provide.

(b) **High Conductivity and Efficiency**

(i) One of the key properties that is ideal for antenna systems is its high electrical conductivity. Galinstan and Mercury's conductivity is comparable to that of copper, one of the most widely used materials in antenna designs.

(ii) High conductivity is essential for efficient signal transmission, where minimizing signal loss and maximizing efficiency are of paramount importance.
(iii) The fluidic nature allows these to be manipulated within a micro-fluidic channel to dynamically alter the antenna's size, shape, and structure, thus enabling real-time performance optimization.
(c) **Non-toxic and Safe**
(i) Unlike mercury, another liquid metal often considered for use in reconfigurable antennas, Galinstan is non-toxic, which is a significant advantage. Mercury's toxic nature poses substantial health and environmental risks, limiting its use in many applications. In contrast, Galinstan is much safer for both users and the environment, rendering it a more viable alternative for large-scale and widespread adoption in reconfigurable antenna systems.
(ii) This property makes Galinstan a more sustainable and practical choice in developing antenna systems for a variety of applications, from telecommunications to medical devices and wearable electronics.
(d) **Integration with Micro-fluidics**
(i) These metal’s liquid state at room temperature is made even more powerful when integrated with micro-fluidic technology. Micro-fluidics refers to the manipulation of fluids in small, precisely controlled channels. In the context of antenna design, micro-fluidics allows for the precise control and distribution of Galinstan within an antenna structure. By adjusting liquid metal's volume in micro-fluidic channels, geometry of the antenna can be dynamically altered, enabling features such as frequency tuning, beam steering, and polarization adjustments. This capability is essential in modern communication systems where antennas must adapt to varying frequencies and environmental conditions.
(ii) In a typical liquid metal antenna design, micro-fluidic channels are incorporated into the antenna structure, and Galinstan is introduced into these channels. The flow can be adjusted by controlling the input and removal of the material from the channels, thereby modifying the antenna's physical shape and, consequently, its electromagnetic properties. This seamless, fluidic manipulation offers significant advantages over traditional methods of antenna reconfiguration, such as electronic switches or mechanical adjustments, which can introduce delays, complexity, and power consumption.
(e) **Reconfigurability and Versatility**
(i) The most significant advantage of integrating with micro-fluidic systems is the reconfigurability it offers. Unlike fixed antennas or those with discrete switching elements, Mercury/ Galinstan-based antennas can be continuously adjusted, allowing them to work efficiently across various frequency bands. This level of adaptability is critical for modern wireless communication systems, like 5G and IoT, where antennas need to support a wide range of frequencies and signal types. Ability of changing antenna’s structure in real-time provides a level of flexibility and efficiency that conventional antenna designs simply cannot match.
(ii) In conclusion, Mercury/ Galinstan’s unique properties—high conductivity, and ability to remain liquid at room temperature—make them an ideal material for reconfigurable antenna systems. Its integration with micro-fluidic technology allows for precise manipulation of the antenna’s geometry, enabling dynamic adjustments to optimize performance. This fluidic reconfiguration provides significant advantages over traditional solid-state antennas, offering superior flexibility, efficiency, and adaptability in a wide range of wireless communication applications.

Background and Literature on Liquid Reconfigurable Antennas

21. Overall, reconfigurable liquid metal antennas utilize reconfiguration techniques that are quite similar to those discussed in above sections for traditional methods. These techniques can be primarily classified into 3 main categories:
(a) Reactive loading
(b) ON-OFF switching
(c) Physical alterations.

Liquid metal is employed for modifying distribution of current within the antenna. As a result, frequency reconfiguration, pattern reconfiguration, polarization reconfiguration, or combination of these elements has been achieved.

22. In Reactive loading technique small quantity of liquid metal is employed for adjusting input impedance of antenna. In a similar manner, liquid metal acts as ON/ OFF switch between various copper metallization. The third method, which entails physical modifications, is the most complex, as it changes the dimensions and/or shape of the radiating element. This approach requires relocating or shifting the liquid metal across various areas, demonstrating the significant flexibility that liquid metals offer in reconfigurability, same would be very difficult to achieve using the traditional methods. In the subsequent subsections, a comprehensive literature review is presented.

III. Design And Development Of Liquid Metal Reconfigurable Wideband & Notch Antenna

Introduction

1. This chapter illustrates how liquid metal slugs can be utilized to link or unlink extensive metal areas, enabling radiation performance that might be unattainable with standard switches. The antenna showcases its ability to reconfigure through the use of straightforward micro-fluidic channels. The suggested antenna is capable of connecting- disconnecting the ground plane which helps it in altering bandwidth between ultra-wideband as well as narrowband.
2. The designed antenna works in wide frequency range from 9-18GHz in enabling mercury channels on antennas and disabling Split Ring Resonator (SRR). By enabling SRR channels we can create the Band-Notch in the wide frequency. In the upcoming sub-sections, design, development, analysis, fabrication and measurement of Wideband and Notch antenna using Mercury (Hg) as a reconfigurable element.

Wideband Liquid (Hg) Reconfigurable Band-Notch Antenna

3.**Design Methodology**

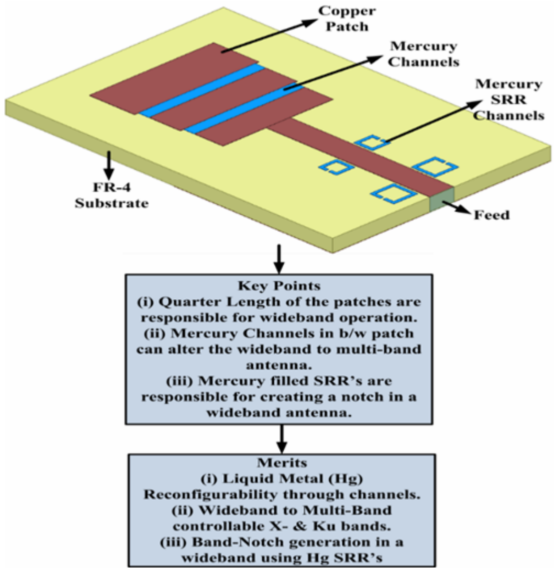


Fig 3-1: Design Methodology of the Liquid Metal Reconfigurable Wideband & Notch Antenna.

Figure 3-1 demonstrates 3D view of proposed wideband & Notch antenna using mercury based liquid reconfigurability. Also discussed few key points in the antenna design and its corresponding merits like wide bandwidth, liquid metal reconfigurability and so on.

4. **Geometry of the Proposed Antenna**

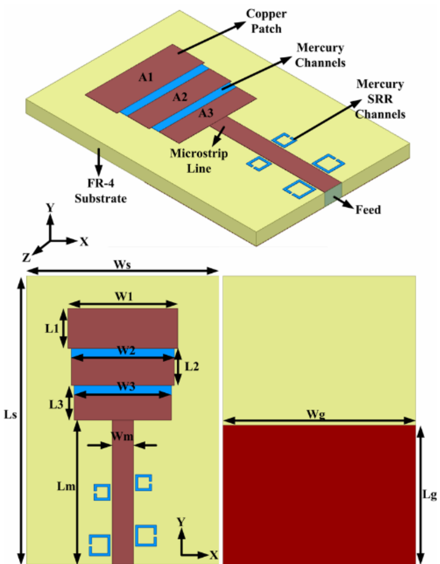


Fig 3-2: Liquid Metal Wideband & Notch Reconfigurable Antenna- 3D View (Upper), Top View (Down right) and Bottom View (Left down).

Figure 3-2 demonstrates geometry of proposed Liquid metal reconfigurable wideband and notch antenna on top of FR-4 glass epoxy substrate having thickness *h* of 1.6mm and dielectric constant of εr=4.4 with a loss tangent *tanδ*=0.02. Ground plane employed in this design is a defected ground plane to attain wider bandwidth instead of full ground plane.

(a) Proposed antenna contains 3 layers where top antenna is placed above substrate and defected ground plane is placed below FR-4 substrate and antenna is excited by employing Microstrip line. The antenna is made of three different copper resonators having different dimensions of L1, L2, L3, W1, W2, W3 and Microstrip line length and width of Lm& Wm. FR-4 substrate exhibiting dimension of Ls &Ws, defected ground plane length and width of Lg&Wg.

(b) The final optimized dimensions are found to be simulated using Ansys HFSS (all dimensions are in mm). The dimensions are to be L1=4.15mm, L2=3.85mm, L3=3.6mm, W1=11.4mm, W2=10.7mm, W3=10.1mm, Ls=30mm, Ws=20mm, Lg=14.5mm, Wg=20mm, Lm=15mm and Wm=2.2mm. There are two pairs of square SRRs opted for creating notch in two different frequencies in case of jamming of that particular slot. These have width and gap of 0.26 mm for both and length and width of 1.69-2.19mm respectively.

5.**Design Procedure of the Proposed Antenna**

(a) Proposed antenna is designed with idea of creating reconfigurability in the frequency initially and adding reconfigurable notching operation to make use of certain frequencies in special applications such that there can reduction in the harmonics in out-of-band frequencies. The antenna initially started from the design equations of patch antenna where it works at a certain resonant frequency (narrow-band) and radiation pattern will be in one direction. Resonant frequency of any antenna is dependent on the half wavelength (λ/2) but when we are interested in wide band configuration, we need to reduce the full ground plane to the half or smaller than the radiating element such that overall size of antenna can be decreased to quarter wavelength (λ/4). Here, the principle of image theory will be applied to the antenna such that your total antenna size is limited and simultaneously increases overall bandwidth of antenna at costing of directional radiation to Omni-directional radiation.

(b) **Step-1:** As mentioned above the antenna design is calculated using patch antenna design equations. We selected three different frequencies for calculating the lengths L1, L2 & L3 of having a quarter wavelength each and corresponding widths W1, W2 & W3.

(c) **Step-2:** Once lengths and widths were calculated the Microstrip line length and width were calculated for 50Ω. Then A1, A2 & A3 are combined with Microstrip line to become wide band antenna. We created a mercury channel separating A1 & A2, A2 & A3, where we can control the wide frequency bandwidth.

(d) **Step-3:** We also added square-based SRRs with liquid configurability where notching is also controllable. SRRs are designed of different dimensions to create a notching at certain frequencies. This band notching will be helpful in certain applications to reduce the harmonics in out-of-band frequencies. Figure 3-3 demonstrates top view of proposed antenna where we show which the copper layers were and which were the mercury micro-fluidic channels.

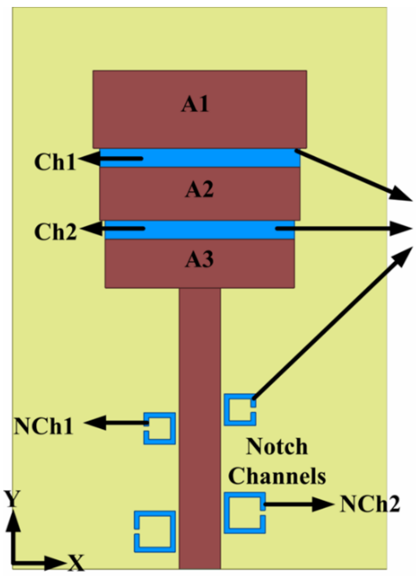


Fig 3-3: Top view of the proposed liquid metal micro-fluidic reconfigurable antenna with mercury channels.

Proposed Antenna Design Analysis

(e) To verify the antenna with different micro-fluidic channels, various simulations have been performed using Ansys HFSS. In each design step, enablement and disablement of the micro-fluidic channels such that how the return loss varies.

(f) **Design-1:** Figure 3-4 shows the proposed antenna with Ch-1, Ch-2 filled with Mercury (Hg) and NCh-1, NCh-2 (SRR Channels) are kept empty. This has created wide band (octave) coverage of whole X- and Ku-Band frequency coverage. Figure 3-4 also demonstrates return loss parameter for corresponding proposed antenna.

(g) From Figure 3-4 it's clear that Ch1 & Ch2 enablement with mercury channels created a wide band width configuration from 9-18GHz with S11 < -10 dB. Hence the return loss (RL) plot from Figure 3-4 clears that there is an impedance bandwidth (S11 < -10 dB) of 9 GHz, which covers military, radar and communication applications.

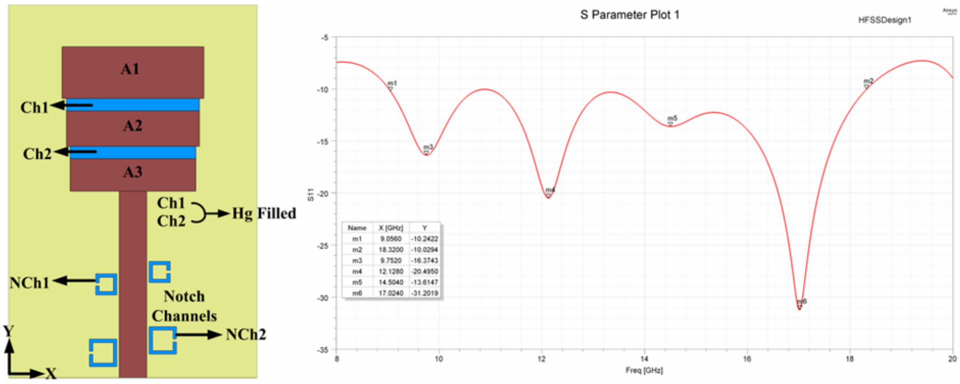


Fig 3-4: Proposed antenna (left) with Ch1 & Ch2 filled with micro-fluid (Hg) in channels and Return Loss (right) covering a wide bandwidth of 9 GHz to 18 GHz.

(h) **Design-2:** In Design-2, Ch-1 is removed with mercury filling and filled Ch-2 with liquid metal (Hg) and SRRs are still not with micro-fluid. Here, the intention is to see the response of a proposed antenna having liquid metal filling. The design is displayed in Figure 3-5 (left) and return loss is demonstrated in Figure 3-5 (right)

(j) From Figure 3-5 it is evident that when disabled Ch-1 in an antenna, we removed the connection of A2 and A3 with A1 such that the resonance at the lower frequencies has been disturbed as demonstrated in return loss plot of Figure 3-5 (right). The upper side of the frequencies almost remains the same particularly resonating at an impedance bandwidth of 2GHz from 16-18GHz. As Ch1 is largest dimension of the radiator, it resembles the lowest frequency of the antenna will be disturbed.

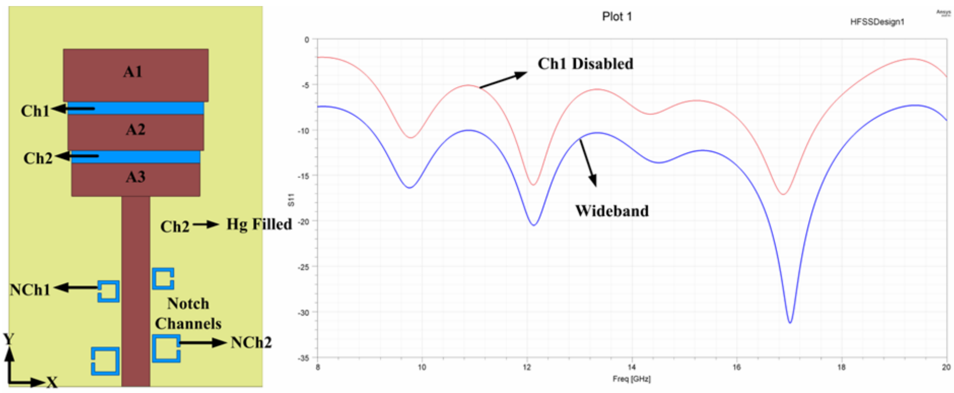


Fig 3-5: Proposed antenna (left) with Ch2 filled with micro-fluid (Hg) in channel and Return Loss (right) covering a limited bandwidth.

(k) In Figure 3-5 (right) blue colour resembles the wideband antenna configuration with Ch1 & Ch2 simultaneously enabled and red colour graph discusses Ch1 disabled resonance.

(l) **Design-3:** In Design-3, Ch-2 is disabled and Ch-1 is filled with Liquid metal i.e., mercury and SRR channels are still not filled with the mercury liquid metal; hence there will be no notching in resonance.

Figure 3-6 (left) demonstrates proposed antenna and (right) side demonstrates return loss (RL) of corresponding design.

(m) From Figure 3-6 it is clear that Ch-1 is filled with the liquid metal and Ch2 is without liquid such that the connection between A1 & A2 has been disconnected with the A3. So, lowest part of the resonances will not occur and higher frequencies will be still enabled. Here from concept of patch antenna design, it is evident that wavelength or length of antenna is inversely proportional to frequency of resonance. Hence, lower size of antenna produces higher frequency of operation.

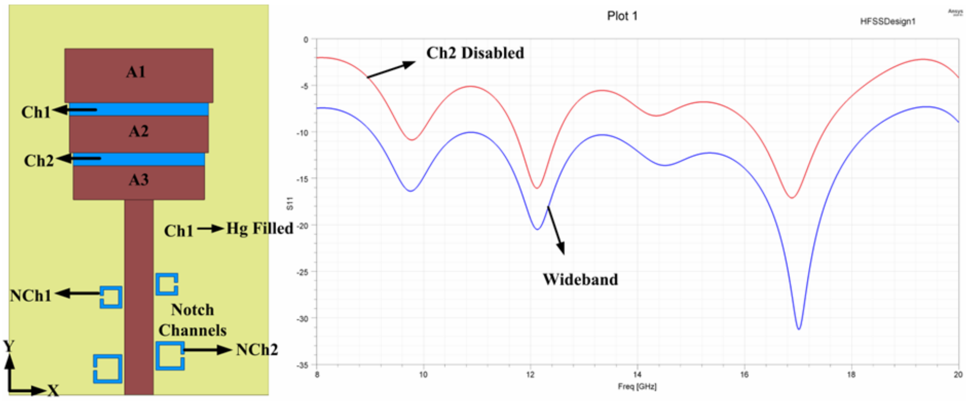


Fig 3-6: Proposed antenna (left) with Ch1 filled with micro-fluid (Hg) in channel and Return Loss (right) covering a limited bandwidth.

(n) **Design-4:** From Design-4, Ch1 and Ch2 will be filled with the liquid metal that is mercury in the band-notch configuration. In band-notch configuration, we will have two different sized SRRs where band-notches at two different frequencies can be achieved by altering NCh1 and NCh2 SRRs simultaneously. In this design, NCh1 is filled with the liquid metal such that a band notch will be created at higher frequency. Figure 3-7 (left) demonstrates design configuration of liquid reconfigurable band-notch antenna at higher side of the frequencies.

(o) Return loss plot is demonstrated in Figure 3-7 (right) where band-notch happened at 17GHz as liquid-metal (Hg) is excited to small SRR on top side ring. Band notch configuration in the design creates the advantage of reducing harmonics, IMD and so on due to the power amplifiers.

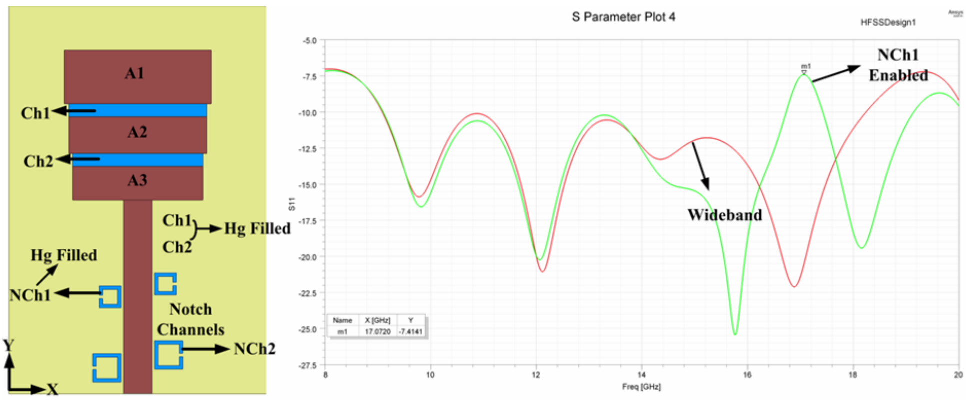


Fig 3-7: Proposed antenna (left) with NCh1 excited with micro-fluid (Hg) + Ch1 & Ch2 (Hg) in channel and Return Loss (right) with band-notch at 17 GHz.

(p) **Design-5:** In Design-5, NCh2 is filled with liquid metal for reconfigurability in creating notch in another frequency than in Design-4 and NCh-1 will be removed with mercury. As we are creating a notch in wide band configuration, the Ch1 and Ch2 will be with Liquid metal (Hg) enabled. In this design, NCh2 is filled with the liquid metal such that a band notch is created at lower frequency of wider band. Figure 3-8 (left) demonstrates design configuration of liquid reconfigurable band-notch antenna with NCh2 filled with mercury. With NCh2 enablement the notch is created in wider frequencies which we can observe clearly from the return loss graph in Figure 3-8 (right).

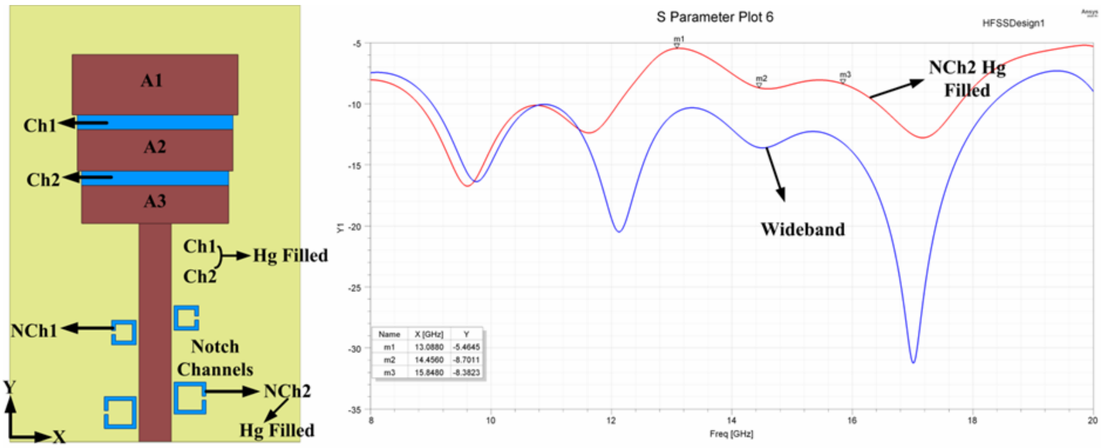


Fig 3-8: Proposed antenna (left) with NCh2 excited with micro-fluid (Hg) + Ch1 & Ch2 (Hg) in channel and Return Loss (right) with band-notch at 13, 14.5, 16 GHz respectively.

(q) Proposed antenna in Figure3-8 is creating wide notch in the antenna from around 13 GHz to 16 GHz of notch bandwidth 3 GHz. This ensures that we can make use of antenna at the desired resonances.

6. Results and Discussion

(a) In results and discussion, we are going to have measured results of various configurations of the proposed antenna. In these sections, we are mainly focused on discussing about measured results of proposed configurations and comparing them with simulated results.

(b) Parameters that show performance metric of antenna is Radiation Pattern, Return Loss (dB), Frequency Vs Gain and Frequency Vs Radiation Efficiency. As we can't test every parameter for all configurations, we are testing all above parameters for wideband antenna and return loss (S11) only for remaining configurations.

7. Wide-Band Antenna

(a) In this sub-section we are going to discuss measured parameters of wide-band antenna encompassing return loss, radiation pattern, gain and radiation efficiency. Figure 3-9 demonstrates fabricated prototype of proposed wide band antenna having Ch1 and Ch2 filled with mercury (Hg) and Notch SRRs kept unfilled. The fabricated antenna is created with mercury channels by placing UV-exposed resin in between patch configurations of A1 & A2, A2 & A3 as Ch1 and Ch2 as well as resin also placed on the NCh1 and NCh2 SRRs such that it can also be operated for band notch configuration.

(b) In this antenna, Ch1 and Ch2 are only filled with mercury and remaining are unfilled such that a wide band can be attained. Figure 3-9 demonstrated fabricated prototype of proposed antenna and Figure 3-10 demonstrated simulated and measured results of prototyped antenna respectively.

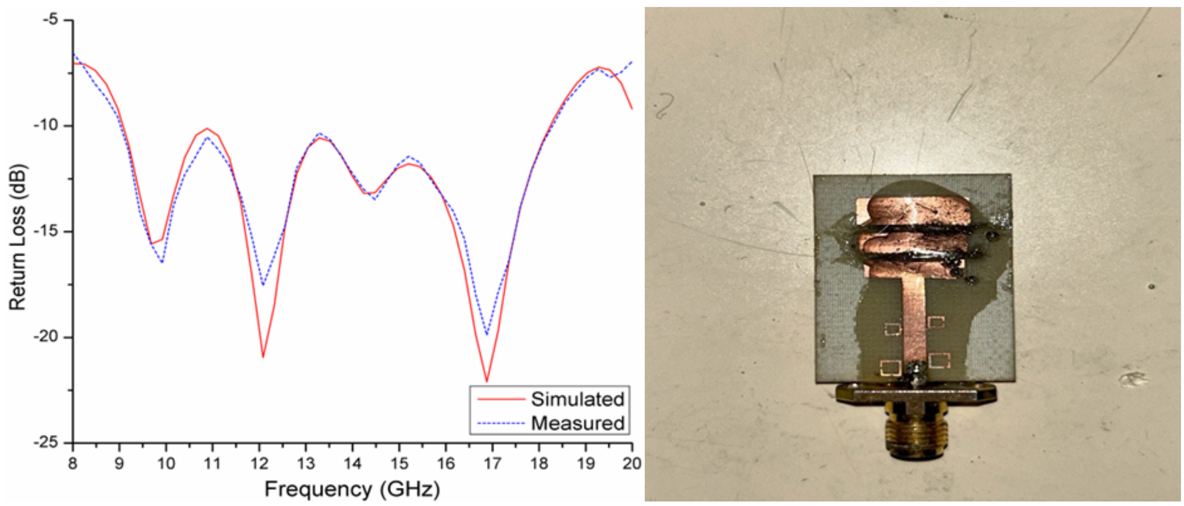


Fig 3-9: Fabricated Antenna Prototype.

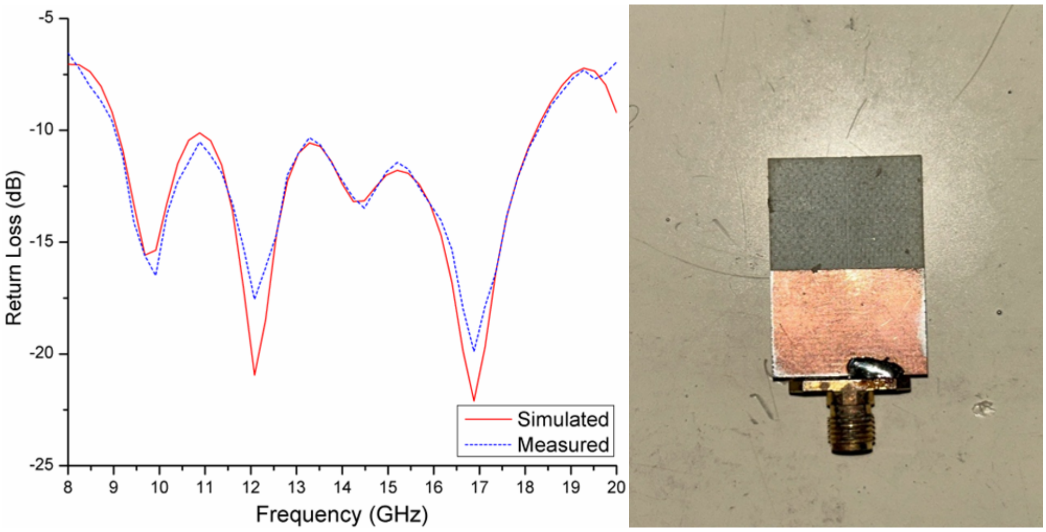


Fig 3-10: Simulated and Measured results of Wide Bandwidth proposed antenna.

(c) From Figure 3-10 it is clear that simulation and measured results are in matching where measured results maintained almost same bandwidth of 8 GHz. The measured results confirm that antenna is working from 8.12 GHz to 17.8 GHz and also due to the fabrication tolerances the antenna results might get slightly deviated. Figure 3-11 demonstrates 3D polar gain plots of antenna at 3 distinct frequencies.

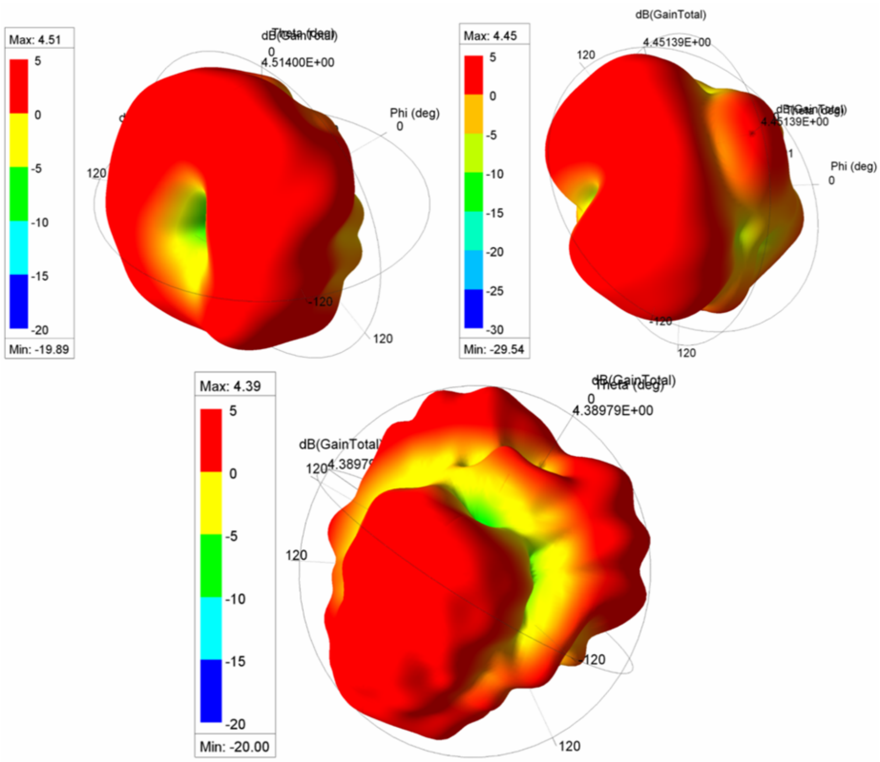


Fig 3-11: 3D Polar Gain Plot of a proposed antenna at 9.8 GHz (Top left), 12.1 GHz (Top right), 16.8 GHz (Bottom Centre).

(d) Figure 3-11shows the 3D- Polar gain plots of proposed antenna radiating at various frequencies 9.8, 12.1 and 16.8GHz with maximum gain of 4.51, 4.45 and 4.39 dBi respectively

(e) Figure 3-12 demonstrates simulated and measured radiation patterns at 9.8 and 16.8GHz respectively. These plots are the 2-D format ones to the above 3-D polar plots. Measured results are in matching to simulated results in two frequencies.

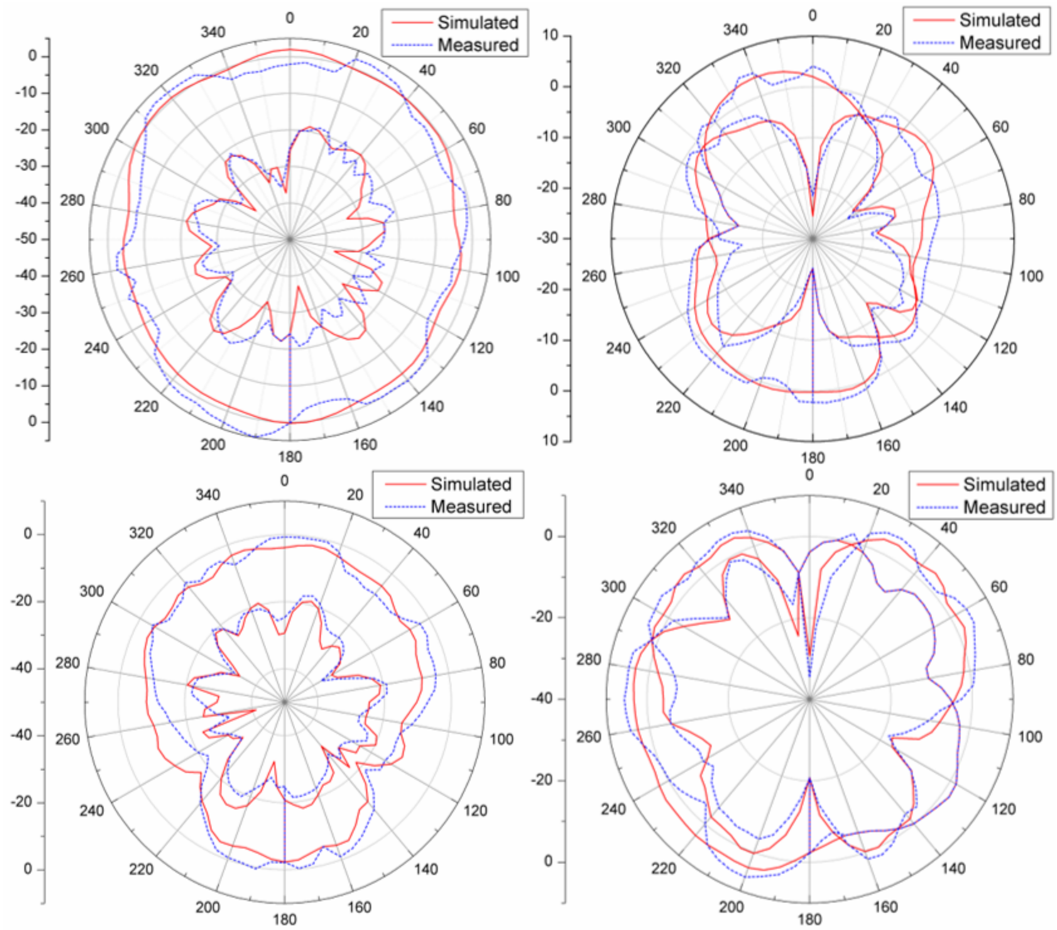


Fig 3-12: 2-D Polar Plots at 9.8 GHz and 16.8 GHz. At 9.8 GHz (Top) E-Plane (Top Left) and H-Plane (Top Right) and at 16.8 GHz (Bottom) E-Plane (Bottom Left) and H-Plane (Bottom Right).

(f) From above figure it is also clear that measured results are in line with simulated results. Small variations might be observed due to fabrication tolerances and measurement doesn't happen in ideal environment. Figure 3-12 demonstrates simulated and measured radiation patterns at 9.8 and 16.8GHz respectively. Radiation Patterns are plotted for E-Plane and H-Plane co-polarization and cross-polarization at two resonant frequencies 9.8 & 16.8GHz which work at a gain greater than 4.4dBi.

(g) Figure 3-13 demonstrates frequency vs peak gain plot where gain is measured across various frequencies. This plot shows simulated and measured frequency vs gain plot and from figure it is also clear that both simulated and measured results are in line with each other and gain is greater than 4 dBi in all wide bandwidth. Figure 3-14 demonstrates frequency vs radiation efficiency plots with comparison between simulated and measured results. Simulated and measured results are in line with each other and also radiation efficiency greater than 80%.

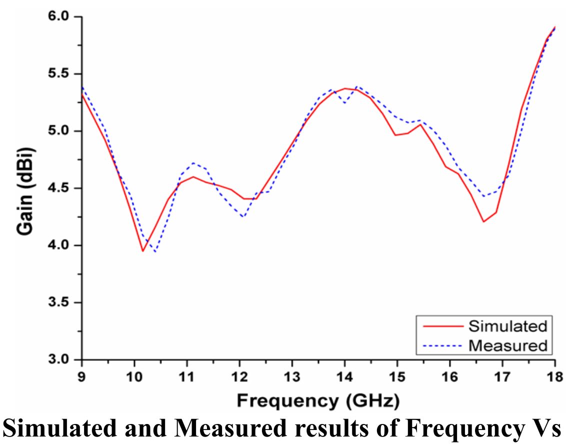


Fig 3-13: Simulated and Measured results of Frequency Vs Gain Plot.

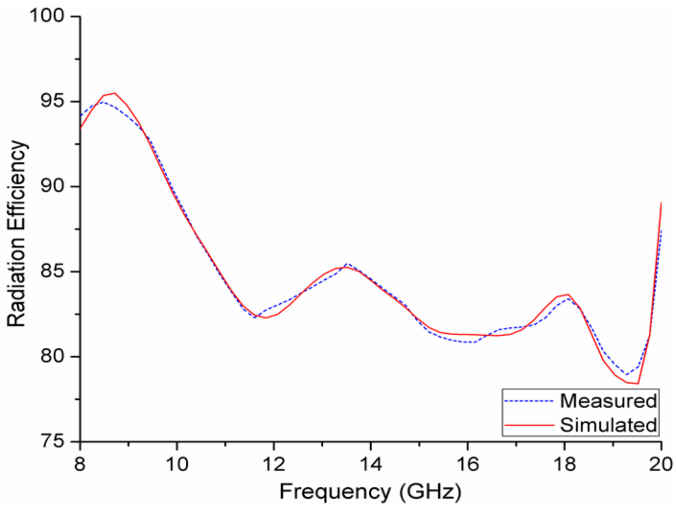


Fig 3-14: Simulated and Measured results of Frequency Vs Radiation Efficiency Plot.

Ch1 Mercury Filled Antenna

(h) In this sub-section we are going to discuss about measured return loss (in dB) of proposed antenna with Ch1 filled with mercury. It has been confirmed from Figure 3-15 that both simulated and measured results are in match.

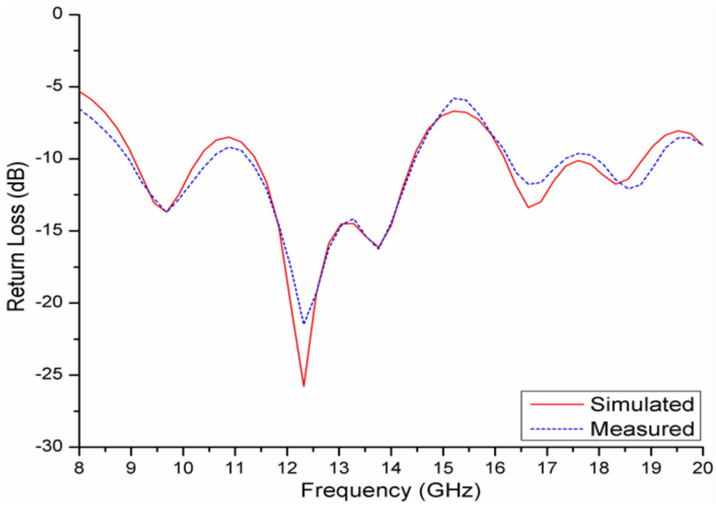


Fig 3-15: Simulated and Measured results of Return Loss for Ch1 Mercury Filled Antenna.

Ch2 Mercury Filled Antenna

(j) In this sub-section, simulated and measured results for Ch2 mercury filled antenna. The proposed antenna is shown in Figure 3-16. From Figure 3-16, both the simulated and measured results are in match and it is also clear that Ch2 discontinued A1 and A2. This makes antenna work on lower frequency side of the band.

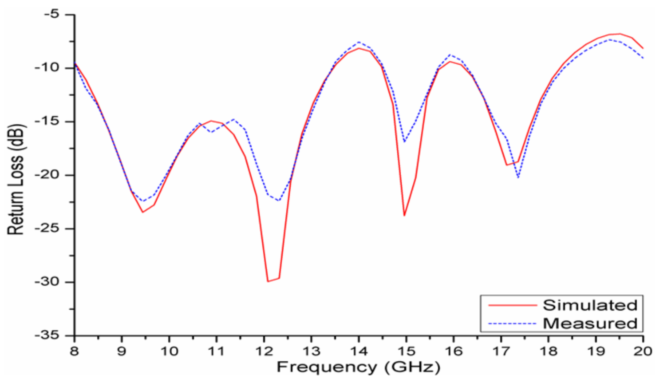


Fig 3-16: Simulated and Measured results of Return Loss for Ch2 Mercury Filled Antenna.

NCh1 SRR's Mercury Filled Antenna

(k) In this sub-section, the Ch1 and Ch2 are filled with mercury such that a wide band configuration can be achieved and from there we can achieve a notch in a band of requirement using SRR filling with mercury. As shown in Figure3-17, simulated and measured results are in line and notch is observed at 17.1 GHz with RL of -6 dB.

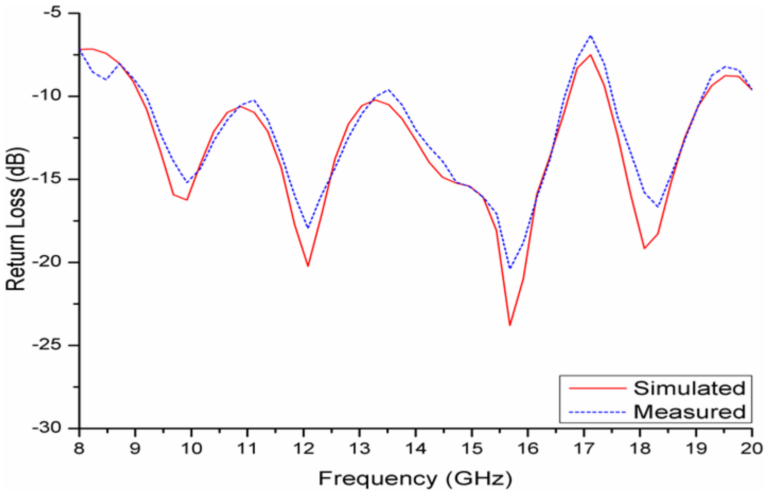


Fig 3-17: Simulated and Measured results of Return Loss for NCh1 Mercury Filled Antenna.

NCh2 SRR's Mercury Filled Antenna

(l) The NCh2 SRRs are filled with mercury whereas larger SRRs are filled with mercury such that the notch will be applied to the lower part of the resonance. When larger SRRs are excited the notch creates wide bandwidth coverage of around 13 GHz to 16 GHz as shown in Figure 3-18.

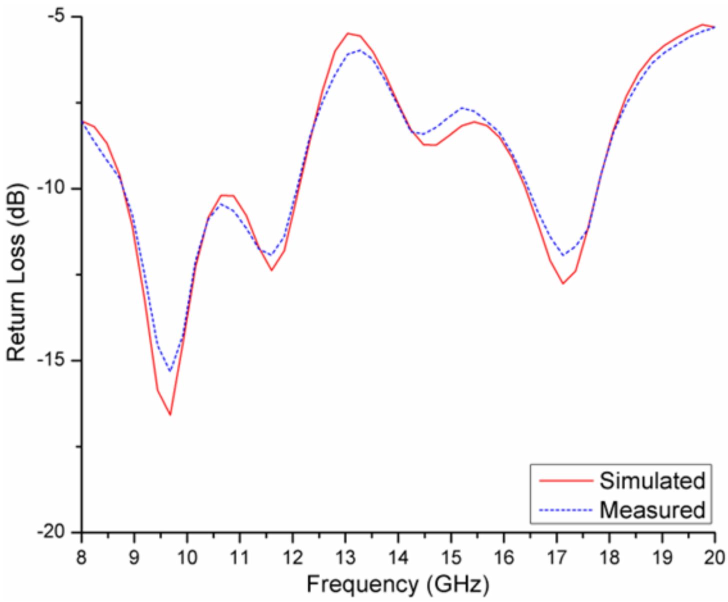


Fig 3-18: Simulated and Measured results of Return Loss for NCh2 Mercury Filled Antenna.

IV. Conclusion

(m) From this chapter it is concluded that proposed antenna works in both X-band and Ku bands and antenna is reconfigurable with micro-fluidic liquid metal like Mercury. The proposed antenna is working on multiple configurations with the help of liquid metal reconfigurability covering in wide bandwidth of 9-18GHz and creating notch in a band using NCh1 and NCh2 SRRs and achieved the notch at 17GHz using NCh1 liquid metal filled and achieving wide band notch from 13-16GHz by exciting NCh2 with mercury.

V. Design And Development Of A Radiation Pattern Reconfigurable Liquid Metal Antenna

Design and Development of a radiation Pattern Reconfigurable Liquid Metal Antenna

1. This chapter illustrates the capability of liquid metal i.e. mercury for reconfiguring radiation patterns in a desired direction. Proposed antenna is designed from concept of Yagi-Uda antenna and it was designed in a planar configuration. The Planar Yagi antenna is also designed with reflectors, feed and directors. The directors in the antenna are responsible for reconfiguring the liquid metal.
2. The designed and proposed antenna works at frequencies ranging from 2.56-2.95GHz. Here, though we are using liquid metal reconfigurability that is not going to affect frequency of operation. In proposed planar Yagi antenna as well the reflector, feeder and director are used and we altered the reconfigurability in directors using liquid metal mercury. The proposed antenna depending on the reconfigurability in directors, radiating in ±15 deg.

Pattern Reconfigurable Liquid (Hg) Antenna

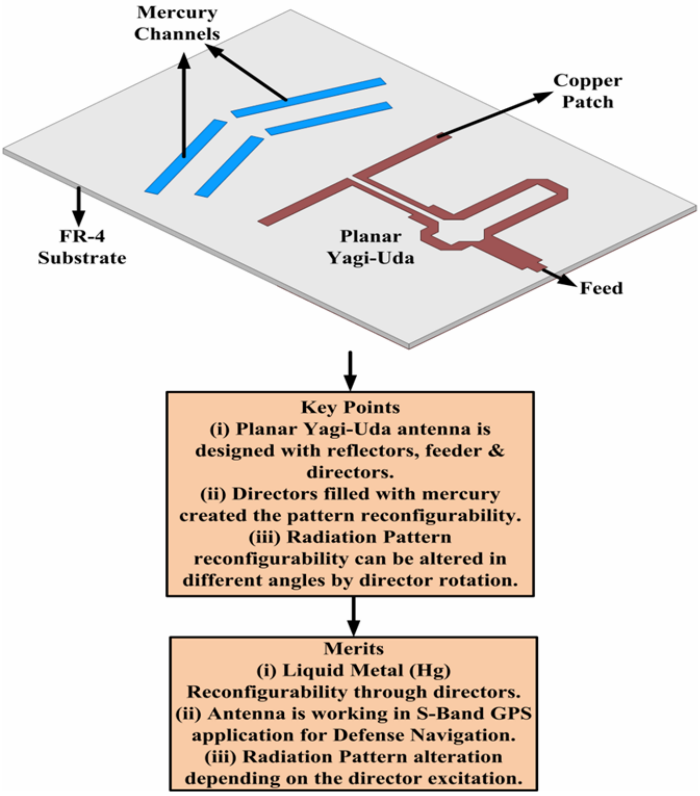


Fig 4-1: Design Methodology of the Liquid Metal Pattern Reconfigurable Antenna.

3. **Design Methodology**

Figure 4-1 demonstrates 3D view of proposed pattern reconfigurable antenna using mercury based liquid metal. Also discussed few key points in antenna design along with its corresponding merits in attaining pattern reconfigurability using liquid metal and continuous transition in radiation.

4. **Geometry of the Proposed Antenna**

(a) Figure 4-2 shows geometry of proposed Liquid metal Pattern reconfigurable antenna on top of FR-4 glass epoxy substrate having thickness *h* of 1.6 mm and dielectric constant of εr = 4.4 with a loss tangent $tan\delta$ = 0.02. The ground plane used in this design is a defected ground plane to make it use that ground plane as a reflector for the back-scattered wave.

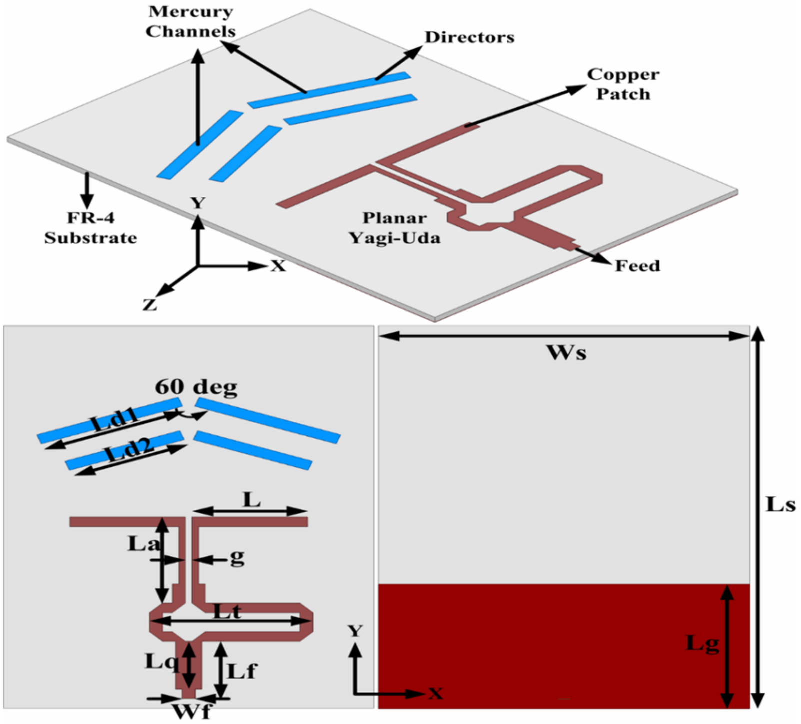


Fig 4-2: Liquid Metal Pattern Reconfigurable Antenna- 3D View (Upper), Top View (Down right) and Bottom View (Left down).

(b) Proposed antenna contains 3 layers where top antenna is placed above substrate and a defected ground plane is placed below FR-4 substrate and antenna is excited by employing Microstrip line feed network with Balun. Proposed Yagi-Uda antenna is a dipole module having differential input such that a Balun must be introduced to convert single-ended Microstrip line to differential line. The Yagi-Uda antenna is divided into three parts which are radiator, reflector and director. The proposed antenna with three different parts having different dimensions of L, and W are radiator (dipole) length and width, g gap b/w dipole, La &Wa denote length and width of differential lines, Lt and Wt denote length and width of balun, Lq&Wq are length and width of quarter-wave transformer and Lf&Wf are length and width of a feed line. FR-4 substrate has dimension of Ls &Ws, defected ground plane length and width of Lg&Wg. Final optimized dimensions are found to be simulated using Ansys HFSS (all dimensions are in mm). The dimensions are to be L=26.5mm, W=3mm, g=1.5mm, La=30mm, Wa=1.5mm, Lt=37.5mm, Wt=3mm, Lq=15mm, Wq=6mm, Lf=3mm, Wf=3mm, Lg=39mm Wg=85mm, Ls=120mm and Ws=85mm. Figure 4-2 demonstrates 3D view of proposed Pattern reconfigurable liquid metal antenna.

5. **Design Procedure of the Proposed Antenna**

(a) Proposed antenna is designed with idea of creating reconfigurability in the radiation pattern and adding director channels as the reconfigurable elements. Proposed antenna takes reference from legacy Yagi-Uda antenna which is divided into three parts named radiator, reflector and director. The dipole antenna is a radiator designed for half wavelength ($\lambda/2$) with centre frequency around 2.6 GHz. Again, here the dipole has differential input so we used a balun for converting single-ended RF input to the differential output where we used quarter wave transformer to match the single-ended impedance with differential impedance. Partial ground plane acts as reflector for dipole antenna to radiate the signal in broadside direction. The third one is a director where which will direct the radiation to forward side and it will also match the wave impedance to the air impedance of 377 ohms. This director also plays a key role in shifting the radiation pattern in multiple beams. So, here we created a pair of two director channels on each side which are divided with 60deg shift angle. This created a beam shifting towards -15deg if left side channels are filled with liquid metal and antenna is radiating at +15deg if right side channels are excited with mercury.

(b) **Step-1:** The proposed antenna has been designed by taking legacy Yagi-Uda antenna into consideration and design equation for the planar dipole radiator is half of guided wave length. Another important thing is dipole antenna is a differential line-fed antenna and it converted to single-ended line to feed by RF source.

(c) **Step-2:** The partial ground plane is another key element in reflecting the back-scattered radiation to the front side. It also makes sure that antenna is radiating in broadside direction. The final element is a director which directs the front scattered data to further front. In this proposed configuration directors are the elements responsible for the reconfigurable radiation pattern.

(d) **Step-3:** Two pairs of directors are placed on each side of the dipole in an angle of difference between them is 60deg. These directors on each side can be excited with liquid metal mercury to reconfigure the radiation pattern. If left side of the directors is excited with mercury, the radiation beam occurs at -15deg and right side directors is excited then radiation beam will occur at +15deg.

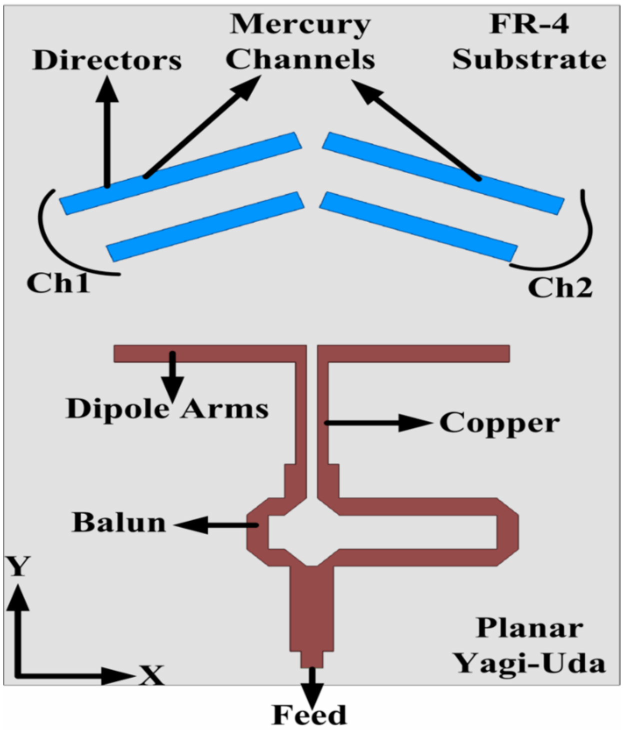


Fig 4-3: Top view of the proposed liquid metal micro-fluidic radiation reconfigurable antenna with mercury channels for Directors.

Proposed Antenna Design Analysis

(e) For validating the proposed antenna with radiation reconfigurability with different micro-fluidic channels, various simulations have been performed using Ansys HFSS. In each design step, enablement and disablement of the micro-fluidic channels make sure that the variation in radiation pattern can be observed. In this proposed antenna nowhere the return loss (RL) (in dB) will not be changed and it is constant, hence return loss plot isn't shown in every design step and is only shown in Figure 4-4.

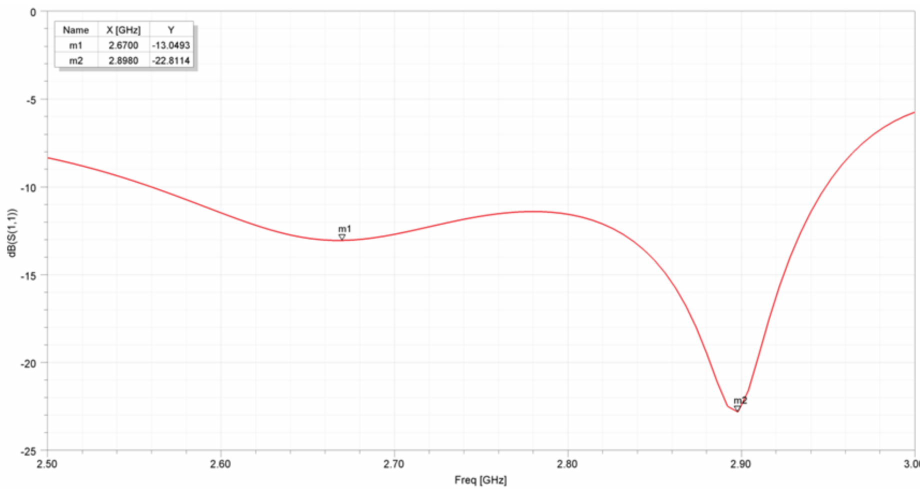


Fig 4-4: Return Loss (in dB) of the Proposed Radiation Pattern Reconfigurable Yagi-Uda Antenna.

(f) **Design-1:** For the understanding of how the radiation pattern is shifted, we are taking the reference Yagi-Uda antenna is simulated with directors at centre to the dipole. Figure 4-5 shows the proposed antenna with directors placed in centre region such that the radiation is at the broadside direction means both elevation and azimuthal planes at 0deg. Figure 4-5 also shows the radiation pattern in broadside direction with a gain greater than 5 dBi at frequency of 2.68GHz.

(g) In this design as well the return loss is similar to the above plot shown in Figure 4-4 with bandwidth coverage of 400MHz from 2.5-2.9GHz. Here, in this design two directors are at centre and mercury is filled in the centre directors such that the radiation is at broadside (ϕ = 0deg & θ = 0deg).

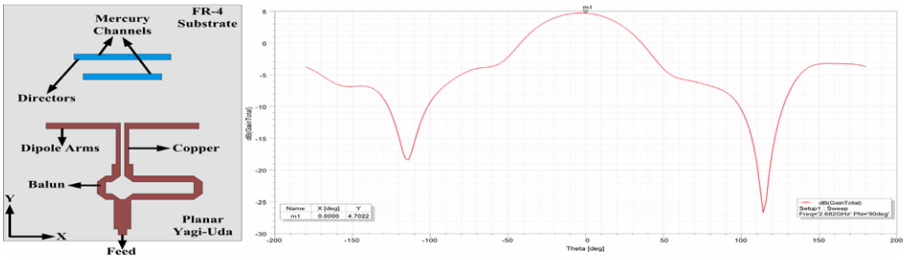


Fig 4-5: Proposed Radiation Pattern Reconfigurable Yagi-Uda Antenna with broadside director (left) and Radiation Pattern in broadside direction at ϕ = 90deg and θ = 0deg (left).

(h) **Design-2:** In Design-2, Ch-1 is filled with mercury and Ch-2 is removed with liquid metal (Hg). When Ch1 is filled with mercury the metallic directors will be on left side such that the radiation will be at -15deg with gain greater than 5dBi at 2.68GHz. In this design as well, there is no change in a radiator hence the return loss will not be changed. The radiation pattern due to the excitation of Ch1 will create gain at θ = 0deg and ϕ = 90deg. Figure 4-6 also shows the radiation pattern plot comparison with broadside radiation pattern.

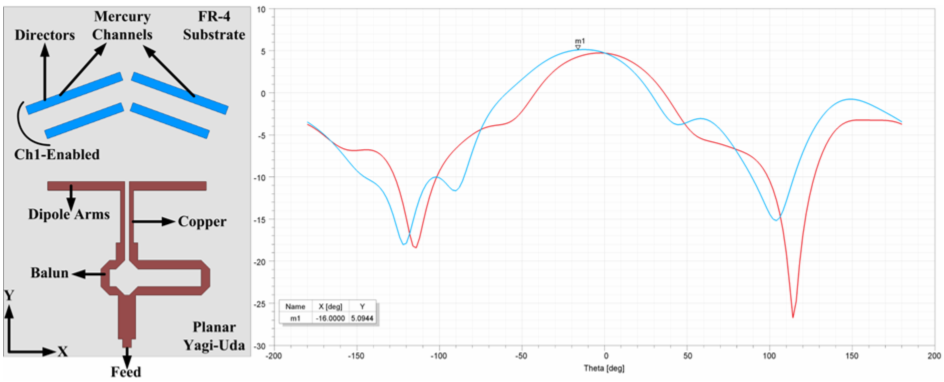


Fig 4-6: Proposed Radiation Pattern Reconfigurable Yagi-Uda Antenna with Ch1 director enabled (left) and Radiation Pattern in broadside direction at ϕ = 90deg and θ = -16deg (left).

(j) **Design-3:** In Design-3, Ch-2 is filled with liquid metal mercury and Ch-1 is un-filled with liquid metal. When Ch2 is filled with mercury on right side directors such that the radiation is on the right side at an angle of +15deg at a gain greater than 5 dBi at 2.68 GHz. Figure 4-7 gives a comparison of radiation pattern plot of broadside radiation with θ = +16deg and ϕ = 90deg.

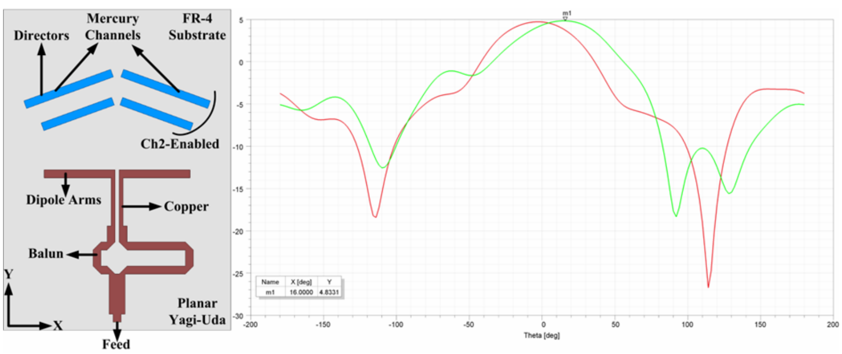


Fig 4-7: Proposed Radiation Pattern Reconfigurable Yagi-Uda Antenna with Ch2 director enabled (left) and Radiation Pattern in broadside direction at ϕ = 90deg and θ = +16deg (left).

VI. Results And Discussion

(a) In results and discussion, we are going to show measured results of two radiation pattern reconfigurability configurations of the proposed antenna. In these sections, we are mainly focused on discussing about measured results of proposed configurations and comparing them with simulated results.

(b) Parameters that show performance metrics of antenna are return Loss (dB), Radiation Pattern reconfigurability, Frequency Vs Gain and Frequency Vs Radiation Efficiency. As this proposed antenna is mainly designed for pattern reconfigurability Return Loss (S11), Frequency Vs Gain and radiation efficiency are measured for one configuration and shown in 4.3.1 sub-section as common parameters.

7. **Common Test Parameters**

(a) In this sub-section common measured parameters of pattern reconfigurable antenna encompassing return loss, radiation pattern, gain as well as radiation efficiency will be discussed. Figure 4-8 demonstrates fabricated prototype of proposed pattern reconfigurable antenna with either Ch1 or Ch2 filled with mercury (Hg) with same return loss, frequency vs gain and radiation efficiency plots. Fabricated antenna is created with mercury channels by placing UV-exposed resin on the place of directors to fill and un-fill with the liquid metal via a small capillary tube inserted via the hard resin. The channels are filled with mercury using a syringe but if we are working in real-time environment the motorised filling and un-filling of mercury will occur.

(b) In this antenna, either Ch1 or Ch2 is only filled with mercury. Figure 4-8 demonstrates fabricated prototype of proposed antenna and Figure 4-9 demonstrates simulated and measured results of prototyped antenna respectively.

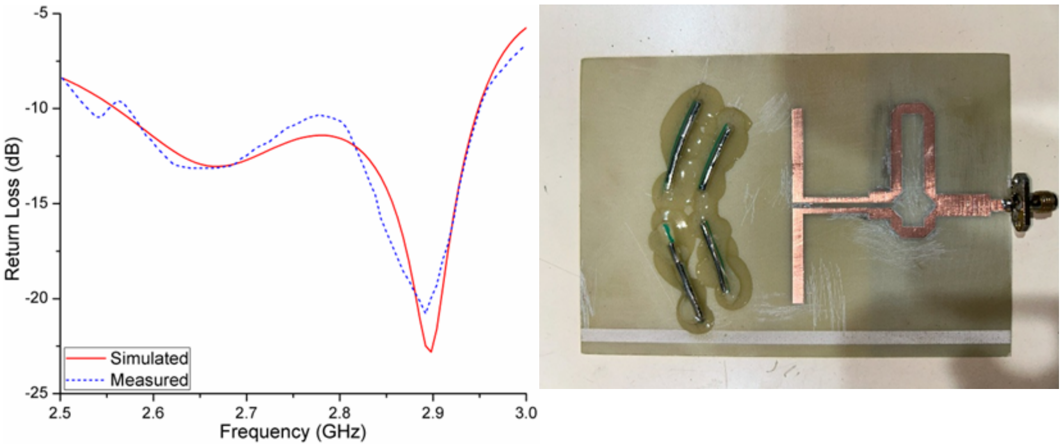


Fig 4-8: Fabricated Antenna Prototype.

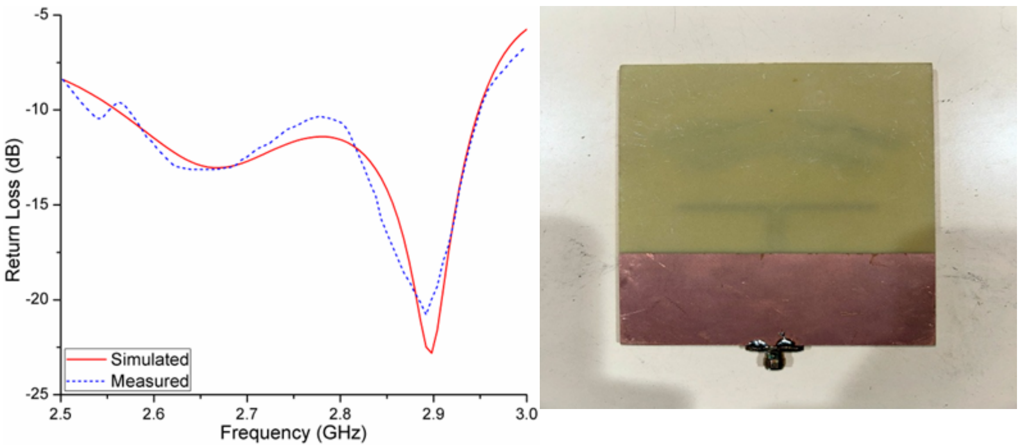


Fig 4-9: Simulated and Measured Return Loss of Pattern Reconfigurable proposed antenna.

(c) Figure 4-10 and Figure 4-11 are comparison plots of simulated and measured results of frequency vs gain and frequency vs radiation efficiency. It is also clear from the results that both simulated and measured results of gain and radiation efficiency are in line with each other.

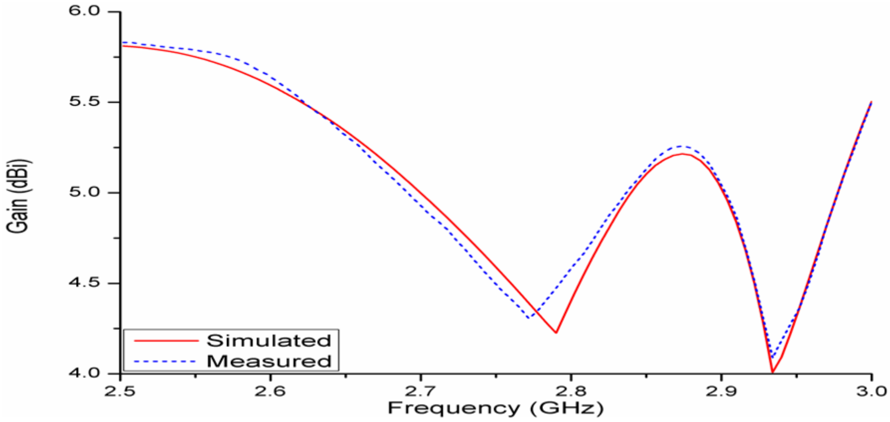


Fig 4-10: Simulated and Measured Frequency vs Gain Plot of Pattern Reconfigurable proposed antenna.

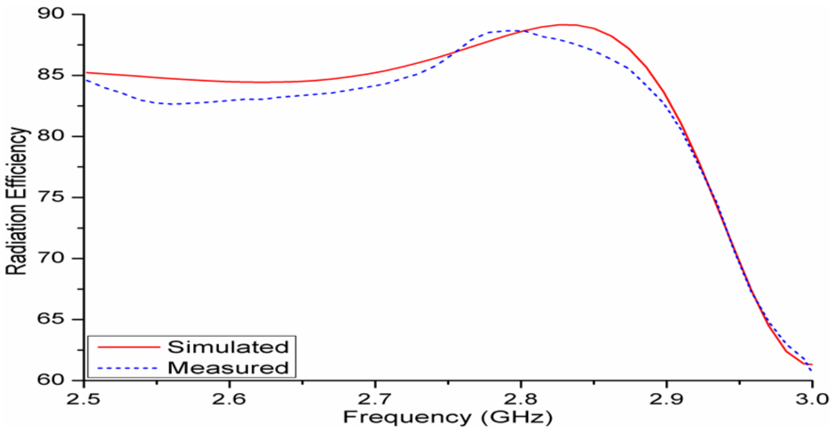


Fig 4-11: Simulated and Measured Frequency vs Radiation Efficiency Plot of Pattern Reconfigurable proposed antenna.

Ch1 Mercury Filled Pattern Reconfigurable Antenna

(d) In this sub-section, measured radiation pattern with gain (in dBi) shifted towards left side that is -16deg elevation plane will be discussed. Figure 4-12 demonstrates comparison of simulated and measured radiation patterns and from plots, it is clear that both simulated and measured results are in line with each other. From measured plots, it is also clear that gain of proposed antenna is maintained at more than 5 dBi.

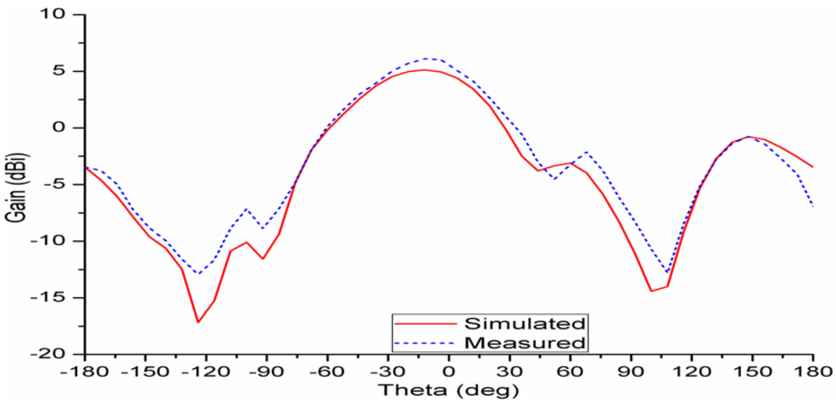


Fig 4-12: Simulated and Measured Radiation Pattern with Ch1 filled with Liquid Metal Mercury.

Ch2 Mercury Filled Pattern Reconfigurable Antenna

(e) In this sub-section, measured radiation pattern with gain (in dBi) shifted towards left side that is +16deg elevation plane will be discussed. Figure 4-13 demonstrates comparison of simulated and measured radiation patterns and from plots it is clear that both simulated and measured results are in line with each other. From measured plots, it is also clear that gain of proposed antenna is maintained at more than 5 dBi.

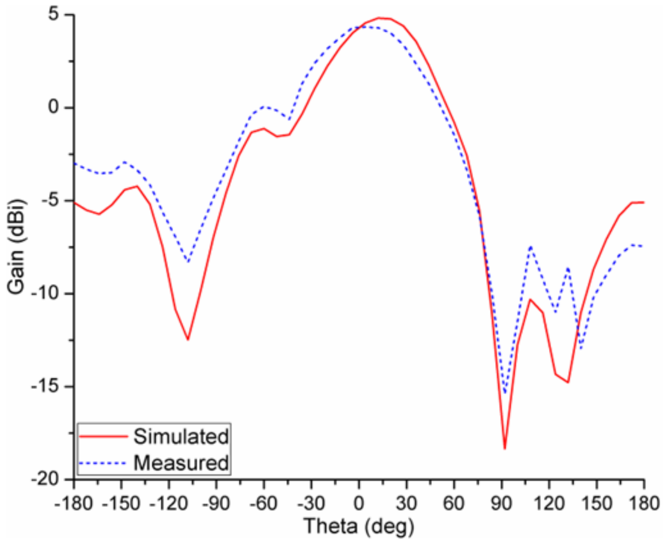


Fig 4-13: Simulated and Measured Radiation Pattern with Ch2 filled with Liquid Metal Mercury.

Conclusion

(f) From this chapter it is concluded that proposed antenna is working in S- band and proposed antenna is a pattern reconfigurable by exciting the directors with liquid metal mercury. From above results, it is evident that antenna is radiating at different beams by depending on the angle of placement of directors and corresponding beam angle is ±16deg.

VII. Conclusion And Future Work

Conclusion and Future Work

1. Due to amalgamation of technologies, the requirement of various adaptabilities/ flexibilities in the modern world was being done using predefined shapes using switches and majority of mechanical components, the same has been made obsolete by the use of liquid metals. These liquid metals have found their applications in wide variety of military fields including EW systems/ Missile technologies and satellite communications. Medical fields have explored the same via wearable body sensors where flexible antennas are highly desirable.
2. The integration of liquid metal antennas in military applications presents notable advantages, particularly in terms of adaptability and performance. These antennas, characterized by their reconfigurable nature, allow for rapid adjustments to frequency and radiation patterns, making them ideal for dynamic operational environments. The use of liquid metal also significantly reduces overall weight of antenna system, which is crucial for deployment on various military platforms, such as unmanned aerial vehicles (UAVs). Furthermore, the innovative design of these antennas can enhance communication capabilities in challenging terrains, ensuring reliable connectivity in the field. As highlighted in recent research, extensive efforts have been made to optimize these systems for multi-band operation, thereby fulfilling essential military requirements. Thus, liquid metal antennas not only bolster military effectiveness but also pave way for advanced technological applications in communications and reconnaissance.
3. These systems allow for dynamic frequency adjustments and adaptable radiation patterns tailored to specific operational environments, thereby maximizing communication efficiency and reliability. As noted in recent studies, the application of liquid metal—due to its excellent conductivity and malleability—enables the antenna structures to be reshaped rapidly, accommodating diverse military needs in real-time scenarios. Furthermore, research suggests the potential amplifications in gain and reduction in size, making these antennas ideal for UAVs in complex communication networks, which require precise performance metrics amid stringent weight restrictions. Ultimately, the functional adaptability of liquid metal antennas empowers military forces to respond to ever-evolving challenges, significantly enhancing the overall operational effectiveness in modern warfare.

Key Findings

1. Liquid metals provide a versatile approach to antenna reconfigurability and can be used in EW systems/ Missile systems/ satellite communication.
2. HFSS simulations validate the feasibility of these designs for real-world applications.

VIII. Limitations

1. The deployment of liquid metal antennas, while promising for military applications due to their reconfigurability and adaptability, faces significant challenges that limit their practical use. One primary concern involves the complexities of maintaining structural integrity under extreme environmental conditions, which can compromise performance and reliability. Moreover, liquid metals present difficulties in fabrication and integration with existing systems, particularly regarding weight restrictions and space availability on various platforms, such as unmanned aerial vehicles (UAVs) that demand lightweight and compact solutions. Additionally, the electrical properties of liquid metals may lead to issues related to impedance matching and signal loss, thereby affecting overall antenna efficiency. As the military seeks to enhance communication capabilities, overcoming these limitations is essential to fully realize potential of liquid metal antenna systems in operational scenarios.
2. The development of liquid metal reconfigurable antenna system for military applications encounters various technical and operational hurdles that must be expertly navigated. One primary challenge lies in the unique requirements surrounding antenna design for UAVs, including constraints on mounting space, weight limitations, and essential radiation parameters, as emphasized in the analysis of microstrip patch antennas for UAV communication. Additionally, achieving operational efficiency necessitates careful optimization of the antenna's geometry and materials to ensure compatibility with multiple communication frequencies while maintaining durability in diverse operational environments. The integration process itself can introduce complications, as variations in performance due to aerodynamic influences must be mitigated. Therefore, addressing these technical and operational hurdles is crucial for the successful deployment of liquid metal antenna systems that can meet the rigorous demands of military operations.
3. The study is mostly dependent on simulation, experimental validation is essential.
4. Challenges in scaling fabrication processes for commercial use.

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