

**RECONFIGURABLE LIQUID-METAL CIRCUITS AND ANTENNAS:
MAGNETIC AND PRESSURE-BASED ACTUATION FOR IMPROVED
PERFORMANCE AT MICROWAVE FREQUENCIES**

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Abstract

Reconfigurable Liquid-Metal Circuits and Antennas: Magnetic and Pressure-Based Actuation for Improved Performance at Microwave Frequencies

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The focus of this thesis is on reconfigurable liquid-metal circuits and antennas designed to operate at radio- and microwave frequencies. Two new actuation methods for manipulating liquid metal, ferrofluidic actuation and pressure-point actuation, are presented. The first method presented, ferrofluidic actuation, utilizes the physical deformation of ferrofluid in response to a magnetic field to displace, or transport, liquid metal from one location to another. This technique is demonstrated and shown in a functional RF switch. The second method described in this work, pressure-point actuation, enables small volumes of liquid metal, referred to as nodes, to be split apart or merged together to incrementally alter the length or shape of a liquid-metal conductor.

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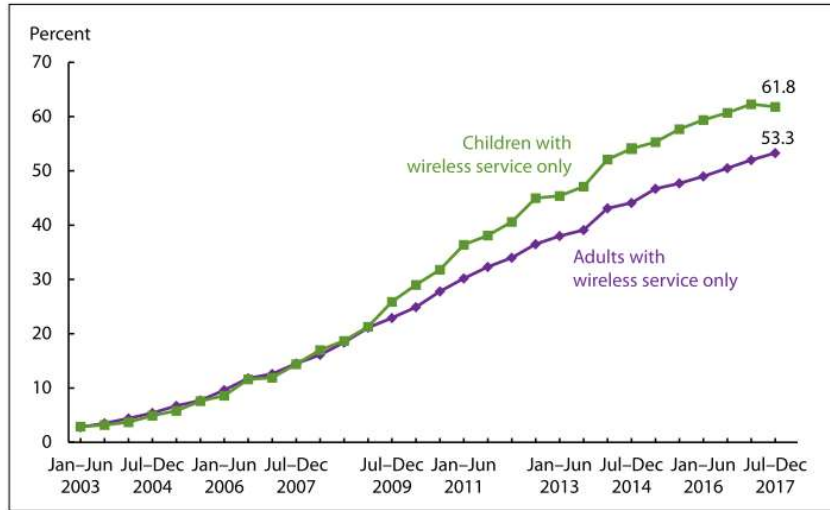
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Chapter 1

Introduction

The innovative competition of the Axis and Allied powers during the mid-20th century birthed a new era and understanding of electromagnetic theory and technologies. Today, wireless technologies, particularly those at radio- and microwave frequencies, play an integral role in virtually every aspect of a developed society. Most obvious perhaps is the unprecedented commercial boom and global proliferation of wireless technologies relating to Internet usage and mobile broadband seen in recent decades [1]–[4].

In developed countries such as the United States, many homes are discarding traditional land-line connections altogether in favor of wireless telephones (also referred to as cell phones or mobile phones) [3]. This increasing trend (Fig. 1.1), inconceivable less than two decades ago, represents not only a global shift in the way users access the Internet, but the telecommunications industry as a whole. In America alone, there are now over 400 million mobile devices translating to roughly 1.2 devices per person, up 56% from just a decade ago [4]. Growth in the number of mobile devices has not kept up with the growth in mobile device data usage, which has risen by over 2,844% since 2010 [4]. Wireless traffic as a whole has grown over 40,000% in the same amount of time [4]. This comprehensive evolution towards wireless dependency has congested the radio-frequency (RF) environment, leaving little room for the inevitable growth of the industry.



NOTE: Adults are aged 18 and over; children are under age 18.
 DATA SOURCE: NCHS, National Health Interview Survey.

Figure 1.1: Percentages of adults and children living in households with only wireless telephone service: United States, 2003–2017 [3].

While peace has led to commercial and cultural enrichment, the origin of the art (i.e. military defense) remains of paramount importance to modern militaries such as that of the United States. To illustrate, in 2013 the U.S. Department of Defense’s strategy for modern warfare explicitly stated their operations in every biome from sea to space were fundamentally dependent on EMS dominance [5], [6]. Needless to say, with 400 million domestic mobile devices and counting, conflicts of interest (and signal strength) have been inevitable. Despite 18% of the EMS between 300 MHz and 3 GHz being reserved for exclusive use by the Federal government, this dependency is in direct conflict with commercial growth, as this is the spectrum most valued by wireless broadband providers [6]. Signal interference, of course, is a primary concern. Interference can occur even without intention, such as one instance in which a brand of garage door openers operated in the same frequency range as Federally reserved frequencies [6]. Widespread adoption of autonomous vehicles will likely provide more opportunities for similar interactions at greater velocities. However, much of the available spectrum is non-reserved and shared between civilian and military

users alike, increasing congestion and the likelihood for interference with mundane or catastrophic consequences. The opposing forces of high demand and innate inflexibility of the EMS require technological solutions to accommodate both the laws of nature and economics. Military strategies demand this in the format of technologies which enable spectrum sharing, technologies which use low-demand frequencies, and those which give access to wider frequency ranges [5], [6]. Commercial ventures require similar advances with less ulterior motives. As a result, unconventional and inventive approaches to solving the saturated EMS environment have been a featured topic of research among those in the radio- and microwave-frequency communities.

1.1 Reconfigurable Technology Overview

Those who wish to improve spectrum sharing and expand operational frequency ranges are likely to have considerable interest in reconfigurable RF circuits and devices. Such devices can modify one or more parameters, often independently, enabling adaptive performance capabilities which may be desired in applications where an operating requirement is unknown or must be satisfied over multiple domains.

One of the most recurrent devices used in performance tuning is what is known colloquially as an RF switch. RF switches inhibit or allow an RF signal to pass and can be used on an individual or collective basis, depending on the complexity of the task. RF switches are typically smaller parts of a greater whole, such as in [7] in which a reconfigurable antenna leverages them to modify its operating frequency. RF switches, like any other physical object, are imperfect and therefore lack the perfect qualities RF theory demands of them (e.g. no insertion loss, infinite isolation, infinite linearity, absolute power handling, instantaneous switching speed, no power consumption, and infinitesimally small [8]). Conventional RF switches can be implemented with field-effect

transistors (FETs), PIN diodes, or more recently microelectromechanical systems (MEMS). MEMS RF switches were developed as a remedy to the nonlinear distortion and losses incurred by the semiconductors. However, the Achilles' heel of MEMS technology is their requirement for high actuation voltages and the complex design criteria associated with micro-scaled mechanical switches operating at micro-Newton forces for millions, sometimes billions, of cycles in the device's lifetime [8].

1.2 Liquid Metal and Liquid-Metal Reconfigurable Technology

One avenue of research which has grown in interest and capabilities is liquid-based RF electronics, enabled by the advent of gallium-based liquid-metal alloys. Lacking the prohibitive toxicity of mercury, gallium-based alloys are safe to use (even shown to have medical applications in targeted drug delivery [9]) and have received special interest in flexible, adaptive technologies due to their high conductivity (relative to mercury), amorphous, and self-healing properties [10]. In RF applications, where performance parameters are often highly geometry-dependent, an amorphous conductive element which can be separated and re-combined without interconnects presents unique possibilities for the RF community. Liquid metal offers new ways of solving old problems, having already been demonstrated as an effective tool in developing number of reconfigurable RF devices such as switches, filters, and antennas, to name a few [11]–[13]. The evolution of actuation methods (i.e. how the liquid metal is moved or re-shaped) has produced a number of available options including pressure, electrical, and magnetic techniques [14]–[21].

1.3 Thesis Organization

In this work, two new methods are introduced as alternatives and expansions of actuation methods for liquid metal. These solutions are intended to improve the simplicity and efficacy of reconfigurable RF devices which use liquid metal as a conductive element.

The first chapter of this work involves ferrofluidic actuation, a new actuation method that uses a hydrocarbon-based ferrofluid (EFH1, Ferrotec Corp.) for actuating liquid metal. The ferrofluid physically deforms in response to an applied magnetic field, allowing a gallium-based liquid metal to be transported within a fluidic channel filled with this ferrofluid. Ferrofluid is compared with another liquid used in state-of-the-art reconfigurable liquid-metal devices to review its performance at radio- and microwave frequencies. The second chapter discusses utilizing ferrofluidic actuation in a functional RF switch. Ferrofluidic actuation is used to displace a droplet of liquid metal from one state to another, turning the switch ON and OFF magnetically. The third chapter of this work involves no magnetic theory whatsoever, but rather simplifies reconfigurability by relying on another new actuation method referred to as pressure-point actuation. In this method which uses pressure in lieu of magnetic fields, interconnected nodes which contain liquid metal can be merged together or split apart. In this manner, the liquid-metal nodes collectively form a larger conductive element which can be lengthened or shortened. The usefulness of this technique is then demonstrated in the form of a frequency-reconfigurable dipole antenna, where the operating frequency of the antenna is dependent on the length of the number of connected nodes. The conclusion of this work, in addition to subsequent research avenues which will be explored as a result, are presented in Chapter 5.

Chapter 2

Ferrofluidic Actuation of Liquid for Radio-Frequency Applications¹

2.1 Introduction

Liquid metals have recently been used in the development of a variety of reconfigurable radio-frequency (RF) circuits [11]–[13]. Such devices typically employ non-toxic gallium-based alloys and use a variety of actuation methods to manipulate the liquid metal to achieve the desired performance.

Electrical actuation of liquid metal offers practical advantages over the use of pumps: reduced size, weight, and power requirements. An example is electrowetting-on-dielectric (EWOD), although this method requires continuous actuation voltages for sustained deformation [14]. Continuous electrowetting (CEW) [15], electrocapillary actuation (ECA) [16] and electrochemically controlled capillarity (ECC) [17] can actuate liquid metal using lower voltages than EWOD. Magnetic fields have also been used to manipulate gallium-based liquid metals [18]–[21]. However, many of the above methods require gallium-based liquid metals to be immersed in a strong acid or base. This removes the oxide skin inherent to gallium-based alloys when subjected to even trace amounts

¹ The work presented in this chapter is based on: A. W. Combs, W. A. Shiroma, and A. T. Ohta, “Ferrofluidic actuation of liquid metal for radio-frequency applications,” 2018 [33].

of oxygen; otherwise the oxide skin adheres readily to many materials, and prevents the liquid metal from behaving as a true liquid. However, these aqueous acidic or basic solutions are lossy at microwave frequencies, meaning that the reconfigurability of electrically and magnetically actuated liquid-metal RF circuits comes with a performance trade-off.

This chapter presents a new method that uses a hydrocarbon-based ferrofluid (EFH1, Ferrotec Corp.) for actuating liquid metal. The ferrofluid physically deforms in response to an applied magnetic field, allowing a gallium-based liquid metal [10] to be transported within a fluidic channel filled with this ferrofluid. The ferrofluid fulfills three important functions: 1) it prevents the oxide skin of the Galinstan liquid metal from adhering to the surfaces of the surrounding fluidic channel; 2) it enables magnetically controlled liquid-metal actuation; 3) it exhibits significantly lower RF loss compared to aqueous solutions.

2.2 Ferrofluidic Actuation of Liquid Metal

Ferrofluids are stable dispersions consisting of magnetic particles coated by a surfactant and suspended in a carrier fluid. In the absence of an external magnetic field, there is no net magnetization of the particles in the ferrofluid. When an external magnetic field is applied, the initially randomized magnetic moments of the particles align with the magnetic field lines, physically deforming the ferrofluid. When the ferrofluid is confined within a fluidic channel, it can form a “wall” that occludes the channel, given that the magnetic field lines are relatively uniform throughout the channel cross-section (Fig. 2.1). When a liquid-metal slug is injected into a ferrofluid-filled channel, it does not stick to the walls of the channel due to the interfacial slip layer provided by the hydrocarbon-based carrier fluid. This is similar to an approach that used water for the same

purpose [22]. As the applied magnetic field moves relative to the channel, the corresponding ferrofluidic wall moves within the channel as well, physically displacing the unanchored liquid-metal slug along with it.

Previous studies have demonstrated the use of ferrofluid for manipulating other liquids for micropumps [23] or for ferrofluid-based droplet microfluidics [24], [25]. However, these studies manipulated nano- and micrometer-scale particles, in contrast to the approach presented here, where a mesoscale volume of dense liquid metal is displaced in a channel using the deformation of the ferrofluid itself. In RF circuits, ferrofluid has been used as a magnetically repositionable dielectric element to realize a tunable RF filter [26]. However, this work focuses on repositioning liquid-metal conductive elements rather than dielectric elements.

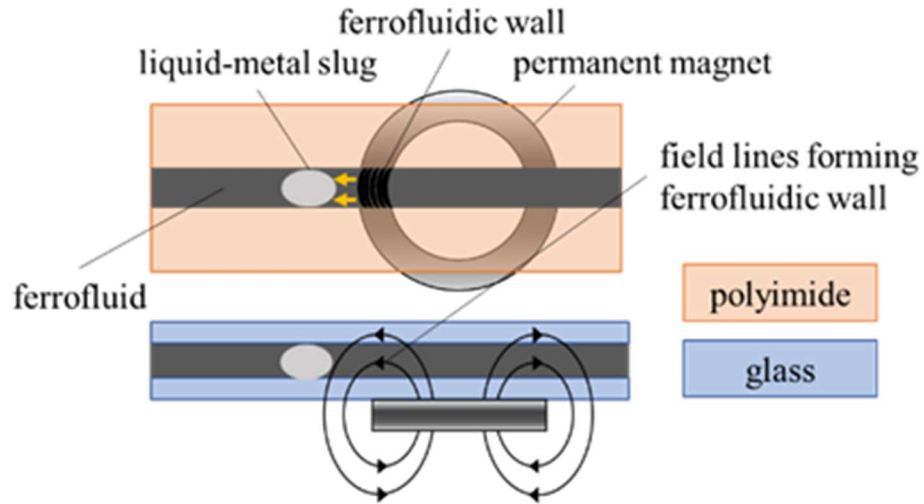


Figure 2.1: Top and cross-sectional views of a channel showing a liquid-metal slug as it is moved through a channel via ferrofluidic actuation.

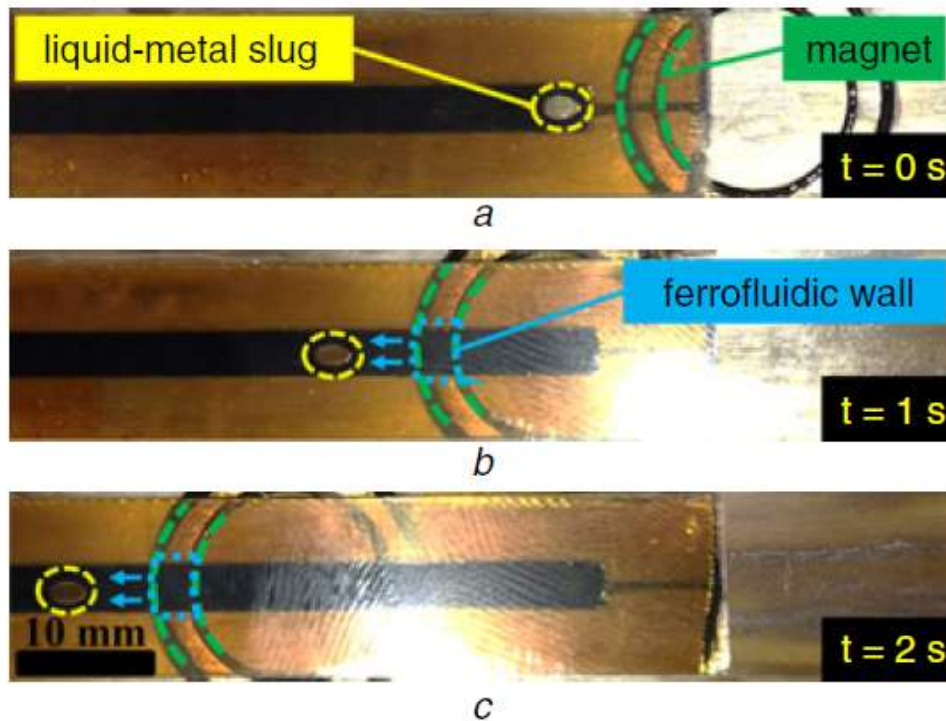


Figure 2.2: Liquid-metal slug (indicated by yellow-dashed lines) moving through straight channel by ferrofluidic wall (blue-dotted lines) as it responds to magnet (green-dashed lines); (a) liquid-metal slug and magnet in initial positions; (b-c) as magnet is moved under channel, ferrofluidic wall forms and displaces liquid-metal slug with $\sim 1:1$ ratio through channel.

2.3 Experimental Results – Ferrofluidic Actuation

To demonstrate the ferrofluidic actuation, a liquid-metal slug is moved through a straight channel as the ferrofluid responds to an applied magnetic field. The channel was fabricated by using polyimide for the channel walls and glass for the ceiling and flooring. The channel height and width were $900\ \mu\text{m}$ and $3\ \text{mm}$, respectively. The channel was filled with EFH1 ferrofluid, and then a Galinstan liquid-metal slug with an approximate volume of $2\ \mu\text{L}$ was injected into the channel. The channel was moved laterally relative to a permanent magnet below the channel (Fig. 2.2). The liquid-metal slug was displaced through the channel at an average velocity of $15.6\ \text{mm/s}$. The

displacement of the liquid-metal slug matches the displacement of the permanent magnet with a ratio of $\sim 1:1$ (Fig. 2.3).

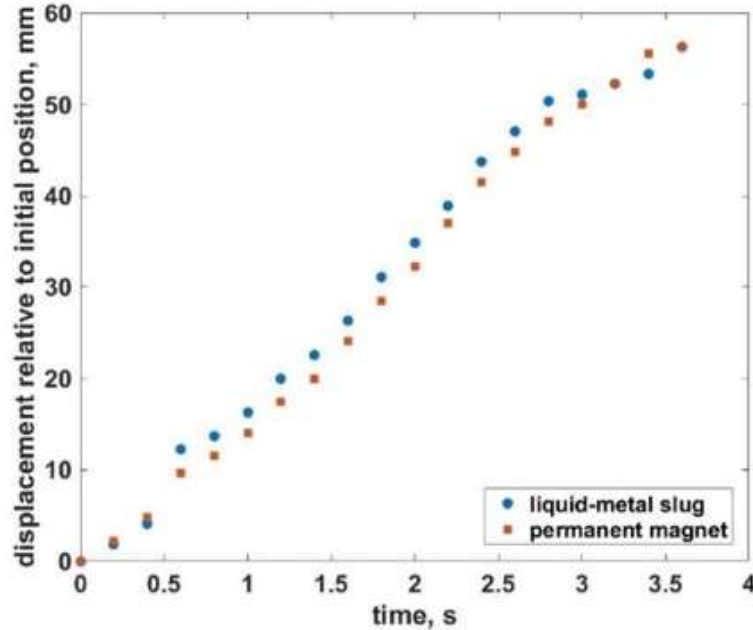


Figure 2.3: Relative displacement of a liquid-metal slug and permanent magnet from their initial positions.

2.4 Experimental Results – RF Loss

To quantify the improvement in RF performance of a ferrofluid over an aqueous solution, a microstrip transmission line was fitted with a microfluidic channel positioned immediately above it (Fig. 2.4). The 50- Ω , 50-mm-long microstrip transmission line was fabricated on 0.787-mm-thick Rogers RT/Duroid® substrate with $\epsilon_r = 2.2$. The microfluidic channel was made of polydimethylsiloxane (PDMS), a flexible silicone elastomer with a reported ϵ_r from ~ 2.95 at 50 MHz to ~ 2.74 at 20 GHz [27]. The PDMS was bonded to the surface of the device using epoxy, forming the walls and ceiling of the channel; the transmission line itself formed the flooring of the channel. The channel was 22 mm long, 2.4 mm wide, and 480 μm high.

The two fluids evaluated using this transmission line were EH1 ferrofluid and 1-M sodium hydroxide (NaOH), which is commonly used in electrical [15], [16], electrochemical [17] and magnetic [18]–[21] actuation methods for gallium-based liquid metals. Insertion and return loss measurements (including the SMA connectors) were taken for three cases: an air-filled channel, a NaOH-filled channel, and an EFH1-filled channel (Fig. 2.5). From 50 MHz to 4 GHz, there is minimal deviation in insertion loss between the three cases. From 4 to 12 GHz, the insertion loss of the NaOH-filled channel begins to deviate significantly from the air-filled channel: its loss increases by an additional 0.57 dB/GHz compared to the air-filled channel. From 12 to 20 GHz, the insertion loss of both the air-filled and NaOH-filled channels increase at a similar rate, though the NaOH-filled channel has an average of >4.70 dB greater insertion loss compared to the air-filled channel over this frequency range. In contrast, the insertion loss of the EFH1-filled channel has little deviation from the air-filled channel. Thus, the EFH1 ferrofluid has no significant effect on the RF performance of the transmission line.



Figure 2.4: Fabricated microstrip line with microfluidic channel; (a) air- and NaOH-filled channel (visually identical in appearance); (b) EFH1-filled channel.

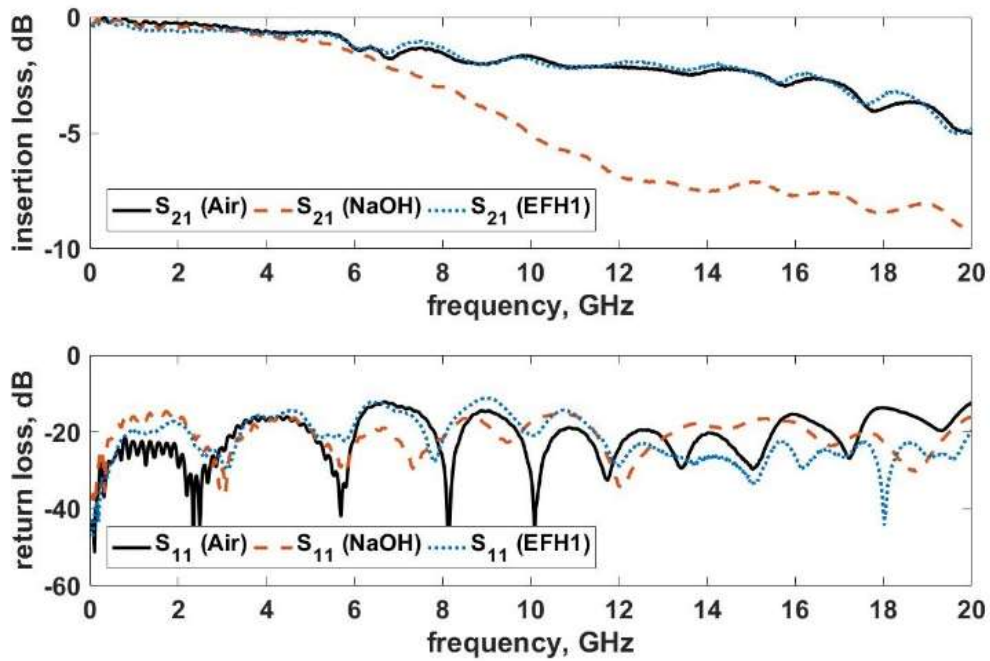


Figure 2.5: Measured insertion and return loss for air-filled (black solid), NaOH-filled (orange dashed), and EFH1-filled (blue dotted) channels.

2.5 Discussion

Using hydrocarbon-based ferrofluids for manipulating liquid metal through a channel can substantially reduce RF losses compared to liquid-metal actuation methods which use lossy aqueous solutions. Many liquid-metal reconfigurable RF devices that use NaOH experience some degradation in performance [28]–[30]. This is primarily due to the high loss tangent of water at microwave frequencies ($\tan \delta = 0.157$ for 25 °C deionized water at 3 GHz [31]). The ferrofluidic actuation described in this chapter simultaneously manipulates the liquid metal, inhibits the sticking of the oxidized liquid metal skin to the channel surfaces, and reduces the RF losses inherent to aqueous solutions. Therefore, existing electrical actuation methods can be replaced with this ferrofluidic actuation, potentially improving the RF performance of reconfigurable liquid-metal circuits.

2.6 Conclusion

A novel magnetic actuation method using ferrofluid to manipulate liquid metal was demonstrated. Furthermore, the hydrocarbon-based ferrofluid was shown to have little effect on the RF performance of a microstrip transmission line. This has the potential to improve the performance of liquid-metal-based reconfigurable RF circuits by replacing existing actuation methods which rely on lossy aqueous solutions. Future work will include further characterization of ferrofluidic actuation of liquid metal, as well as its implementation in reconfigurable RF circuits.

Chapter 3

A Ferrofluidically Actuated Liquid-Metal RF Switch²

3.1 Introduction

The ubiquitous and increasingly complex nature of wireless sensing and communication systems have encouraged the development of reconfigurable RF electronics. These devices offer adaptive performance capabilities, allowing a single device to expand or alter its functionality to meet a desired specification. Recently, interest has grown in using non-toxic gallium-based liquid metals as a fluidic conductor for reconfigurable RF devices [11]–[13]. The fluidic properties of liquid metal allow the conductive element to be reshaped or manipulated, altering the performance of a device such as an antenna [28].

Many of these devices rely on pressure-based actuation for manipulating liquid metal, requiring the use of syringes or external pumps. Electrical actuation of liquid metal offers advantages over pressure-based devices, reducing form factor and power requirements. Electrowetting-on-dielectric (EWOD) is one such method [14], though it requires high actuation voltages which must be applied continuously to maintain only modest deformation.

² The work presented in this chapter is based on: A. W. Combs, K. Kam, A. Ohta, and W. A. Shiroma, “A Ferrofluidically Actuated Liquid-Metal RF Switch,” presented at IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes, Ann Arbor, MI, Jul. 2018 [44].

Alternative electrical actuation methods such as continuous electrowetting (CEW) [15], electrocapillary actuation (ECA) [16], and electrochemically controlled capillarity (ECC) [17] have lower actuation voltages than EWOD. These methods operate by using an electrolytic solution as a medium for manipulation, as well as the removal of an oxide skin innate to gallium-based liquid metals when exposed to oxygen. Removal of the oxide skin is necessary because it adheres to most surfaces, limiting the fluidic properties of liquid metal and preventing manipulation. Magnetic fields have also been used for manipulating liquid metal, though must also be immersed in a strong acid or base for removing the oxide skin [18]–[21]. While critical for actuation, these aqueous electrolytic solutions are lossy at microwave frequencies. Consequently, their use has required additional considerations in the device design to separate the electrolyte from the signal transmission path, such as using air bubbles and capillary rails [32] to minimize losses. If such design considerations were not included, a performance trade-off must be accepted.

In this work, we report a new and promising alternative to existing liquid-metal actuation methods for RF applications. Utilizing the physical deformation of a low-loss hydrocarbon-based ferrofluid in response to an applied magnetic field, a droplet of liquid metal is transported along a guiding track to reconfigure a device. Ferrofluidic actuation enables electrically controlled liquid-metal actuation with significantly reduced RF losses compared to lossy aqueous solutions, eliminates the need for complicated actuation circuits with fluidic channels, and requires no additional power to maintain an actuated state [33]. We demonstrate the technique via a microstrip transmission line serving as a simple RF switch. The RF performance of the ferrofluid is then directly compared to an electrolyte solution commonly used in electrical and magnetic actuation methods.

3.2 Background

Ferrofluidic actuation of liquid metal – demonstrated on an RF device for the first time in this work – is possible because of the combination of three ferrofluid properties: (1) the physical deformation of ferrofluid in response to an applied magnetic field, (2) increased viscosity of the ferrofluid due to the magnetoviscous effect, and (3) the interfacial slip layer provided by the ferrofluid.

Ferrofluids are stable dispersions of ferro- or ferrimagnetic particles coated with a surfactant and suspended in a carrier fluid. The particles are on the order of 10 nm in diameter and therefore possess only a single magnetic domain which is randomly oriented in the absence of an external magnetic field. When an external magnetic field is applied, the magnetic moments align with the field lines, physically deforming the ferrofluid.

In addition to physical deformation, the presence of an external magnetic field causes a phenomenon known as the magnetoviscous effect [34] to occur in a ferrofluid. While the physical mechanisms for the phenomenon remain a focal point of current research, primary factors influencing the extent of the change in viscosity include the size and type of the particles, the magnetic volume concentration of the suspension, as well as the strength of the magnetic field experienced [34]. In concentrated suspensions of ferrofluids (magnetic volume concentration on the order of 10%), viscosity has been experimentally observed to increase to nearly 40% in one study [35] and nearly 200% in another [36].

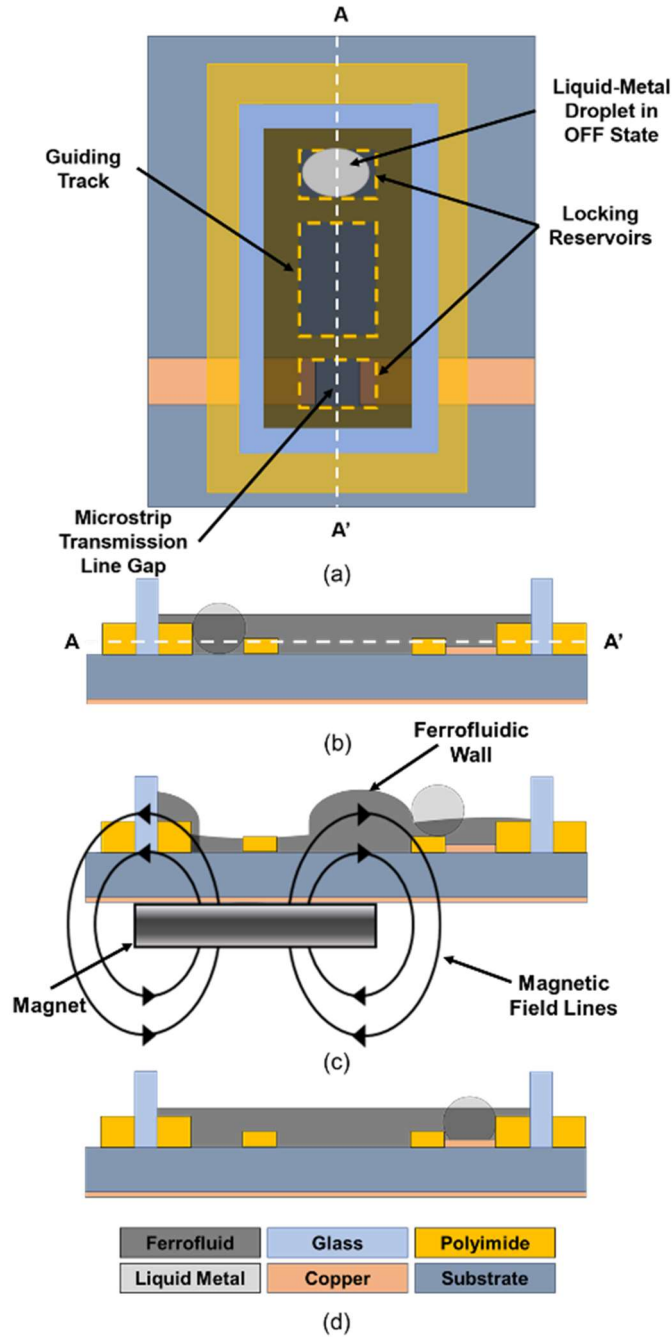


Figure 3.1: Illustrative concept of switch operation: (a) top view of device layout, (b) liquid-metal droplet positioned in OFF state, (c) ferrofluidic wall forms in response to an applied magnetic field, displacing the liquid-metal droplet from its locking reservoir and onto the guiding track, (d) magnetic field removed, liquid-metal droplet positioned in ON state.

Without the presence of a strong acid or base, the formation of the oxide skin on gallium-based liquid metals would typically cause the liquid metal to wet to most surfaces, inhibiting motion. In contrast, when liquid metal is immersed in ferrofluid, it glides freely through a channel or over a surface without sticking. This is possible due to the liquid interfacial slip layer provided by the ferrofluid, similar to a previous study in which water was used for the same purpose [22].

3.3 Design

A. Ferrofluidic Actuation of Liquid Metal

Ferrofluidic actuation of liquid metal is demonstrated with a microstrip transmission line serving as a simple RF switch, as illustrated in Fig. 3.1. Initially in the OFF state, a liquid-metal droplet resides in a locking reservoir. When a magnetic field is introduced, the ferrofluid physically deforms, taking the shape of the magnetic field lines and forming a ferrofluidic “wall” in the channel. As the magnetic field is moved relative to the circuit, the ferrofluidic wall moves with it, effectively displacing the liquid-metal droplet from its locking reservoir to the guiding track. The guiding track provides controlled displacement, guiding the motion of the droplet from its initial locking reservoir to its destination locking reservoir in the ON state. Once the droplet resides in the destination locking reservoir, the magnetic field is removed and the switch remains ON. To switch from the ON state to the OFF state, the actuation process is simply reversed.

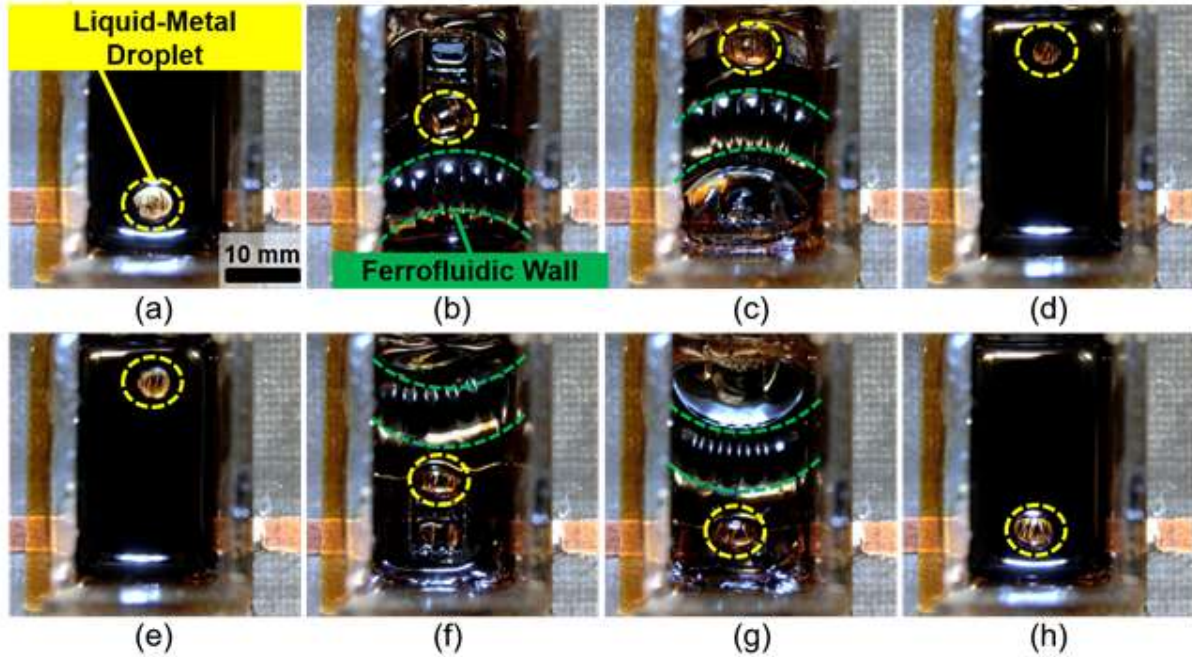


Figure 3.2: Switch operation via ferrofluidic actuation: (a-d) ferrofluidic wall (green dashed) in response to an applied magnetic field, displacing the liquid-metal droplet (yellow dashed) from the ON to the OFF state; (e-h) reverse process.

B. Fabrication

The switch is based on a 50- Ω microstrip transmission line, 50 mm long and 2.4 mm wide, with a 2-mm gap cut at the center. The substrate is Rogers RT/Duroid® 5880 with $\epsilon_r = 2.2$ and a thickness of 0.79 mm. The guiding tracks and locking reservoirs are composed of polyimide tape layers. The guiding track is 6.2 mm \times 3.5 mm, with 600- μ m-thick walls. The locking reservoirs are 2.4 mm \times 3.5 mm and are separated from the guiding track by a 300- μ m-thick layer of polyimide tape. The switch is encircled by 1-mm-thick glass walls bonded and sealed with epoxy, ensuring no leakage of the ferrofluid.

The liquid metal used is Galinstan (commercially available from Geratherm Medical AG). Galinstan is a eutectic gallium-based alloy which remains a liquid from -19° C to 1300° C and has

an electrical conductivity of 2.30×10^6 S/m [10]. The hydrocarbon-based ferrofluid used was EFH1 (commercially available from Ferrotec Corp.).

3.4 Experimental Results

As a baseline measurement, the switch was first measured as an empty fixture filled only with air and a liquid-metal droplet which was positioned using a syringe. To compare the RF performance of a hydrocarbon-based ferrofluid with a lossy aqueous solution commonly used for existing actuation methods for gallium-based liquid metals [15]–[18], the fixture was then filled with 0.1 mL of 1 M NaOH solution. Again, the liquid-metal droplet was positioned in the locking reservoirs using a syringe. The fixture was then flushed with DI water and allowed to evaporate completely. Finally, the fixture was filled with 0.1 mL of EFH1. The liquid-metal droplet was switched between ON and OFF states at a velocity of ~ 2 mm/s via ferrofluidic actuation by manually repositioning a permanent magnet below the device (Fig. 3.2). Insertion loss (Fig. 3.3), return loss (Fig. 3.4), and isolation (Fig. 3.5) measurements (including the SMA connectors) for all three cases were taken from 50 MHz to 20 GHz.

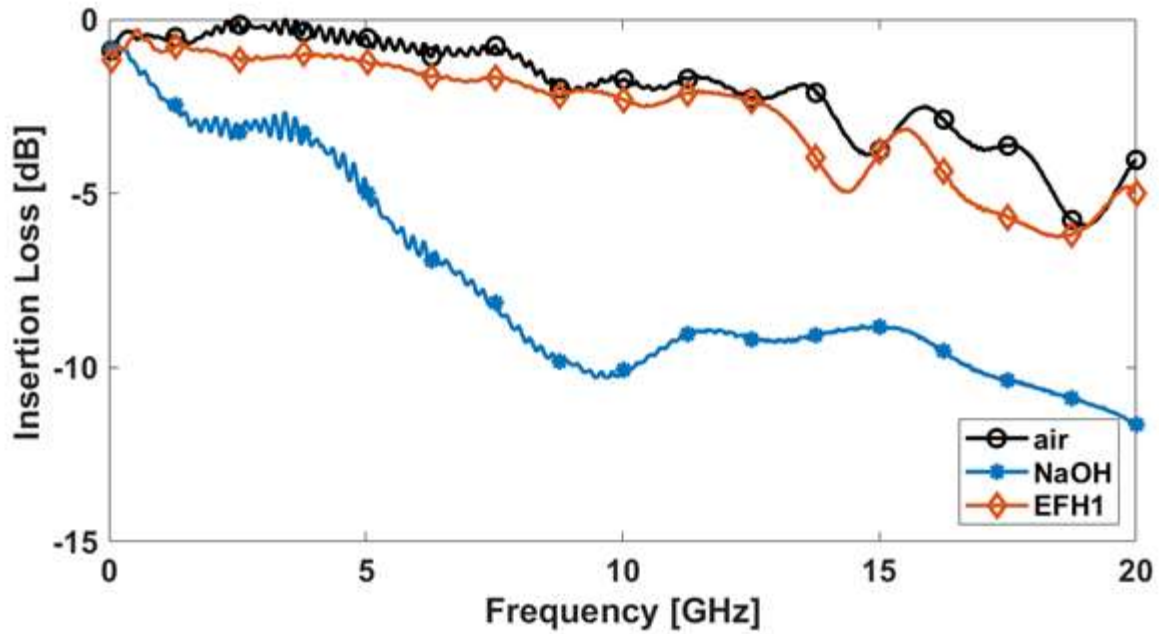


Figure 3.3: Measured insertion loss in ON state for air-filled, NaOH-filled, and EFH1-filled cases.

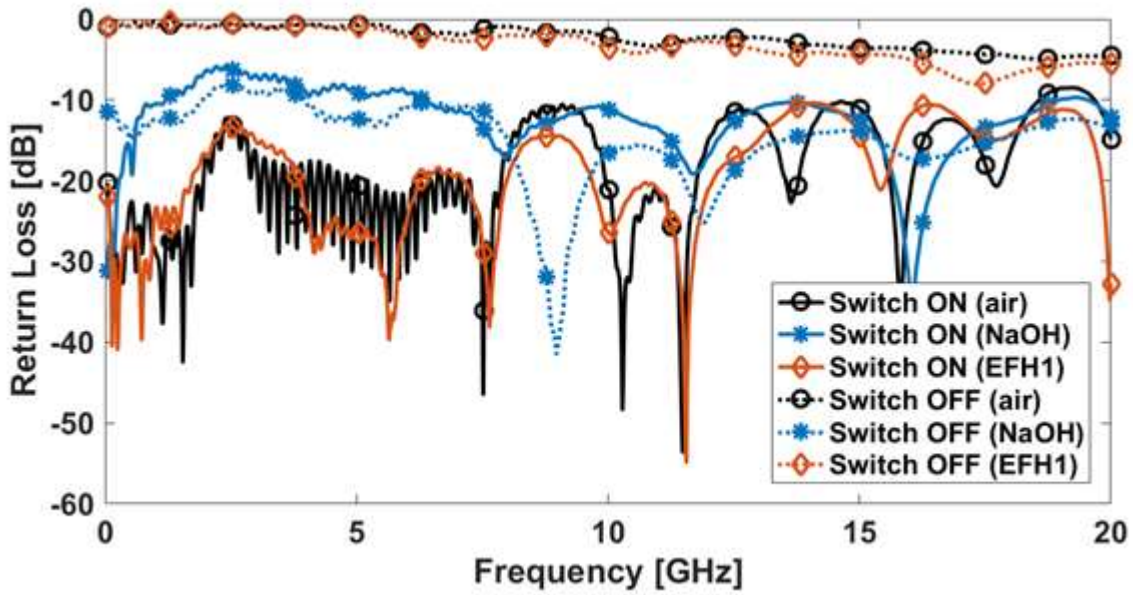


Figure 3.4: Measured return loss for switch in ON state (solid) and OFF state (dotted) for air-filled, NaOH-filled, and EFH1-filled cases.

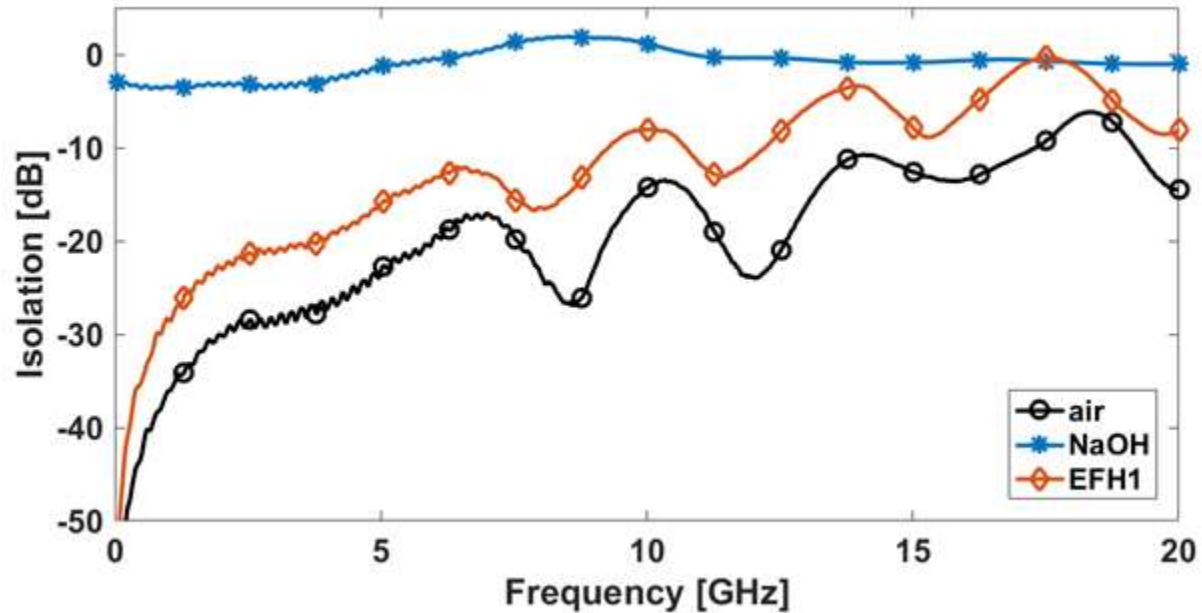


Figure 3.5: Measured isolation for air-filled, NaOH-filled, and EFH1-filled cases.

From 50 MHz to 6 GHz, the air-filled case had less than 1 dB insertion loss. The EFH1-filled case performed similarly, having less than 1.6 dB insertion loss over the same range. From 6 GHz to 20 GHz, the EFH1-filled case contributed an average of 0.8 dB additional insertion loss compared to the air-filled case. In contrast, the NaOH-filled case had up to 6.7 dB insertion loss from 50 MHz to 6 GHz. From 6 GHz to 20 GHz, the NaOH-filled case contributed an average of 6.8 dB additional insertion loss relative to the air-filled case.

Isolation ($S_{21,ON} - S_{21,OFF}$) for the NaOH-filled case was virtually non-existent, averaging less than 1 dB from 50 MHz to 20 GHz and actually exceeding 0 dB at some frequencies. This is because in the OFF state, NaOH is still sufficiently conductive to allow transmission even without a liquid-metal contact. Comparatively, the EFH1-filled case had greater than 20 dB isolation for frequencies below 3 GHz and greater than 10 dB isolation for frequencies below 9 GHz. Return

loss of NaOH in the OFF state is also greater than that of the air- and EFH1-filled cases, indicative of NaOH's lossy properties as it absorbs the incident power.

3.5 Conclusion

A new actuation method for liquid-metal reconfigurable RF circuits was realized using the magnetic response of a hydrocarbon-based ferrofluid. Compared to lossy aqueous solutions used in existing actuation methods, this method reduces RF losses and improves isolation. Additionally, it eliminates the need for actuation electrodes within a fluidic channel, reducing design and fabrication complexities. Future work will involve electrically driven ferrofluidic actuation via electromagnets.

Chapter 4

Frequency-Reconfigurable Dipole Using Liquid-Metal Nodes³

4.1 Introduction

In recent decades, advances in wireless technologies have created a surplus of consumers, further straining the saturated radio-frequency environment. The result of this is an immediate need for next-generation wireless technologies that allow greater per-capita usage of the available spectrum. Thus, reconfigurable radio networks, capable of adapting to an operational need, are preferable to those which are designed to a fixed operating constraint [37], [38]. One approach toward achieving this goal is a terminal reconfigurable antenna capable of altering the physical properties of the radiating aperture.

Previous studies utilizing a MEMS-based approach have demonstrated reconfigurable aperture antennas capable of independent versatility in operating frequency, polarization, and radiation pattern [39]–[41]. This was accomplished using an array of discrete metallic elements, referred to as pixels, interconnected by a series of RF switches which could be selectively turned ‘on’ or ‘off’, collectively forming a metallic radiator with the desired antenna geometry. However, for

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larger arrays the number of required switches quickly becomes unmanageable, as the switches themselves require high actuation voltages to operate and collectively begin to introduce significant insertion loss. In addition, these switches require the constant application of an actuation signal to maintain their ‘on’ state, leading to significant (and continuous) power costs. An alternative to the MEMS-based approach is to attain reconfigurability by replacing both the metallic pixels and switches with liquid metal, capitalizing on its ability to merge with itself and eliminating the need for an accompanying switching network. Liquid metals have shown potential for achieving RF reconfigurability through a wide variety of approaches including pressure-based methods as well as electrical and magnetic methods [14]-[21].

In this chapter, a liquid-metal frequency-reconfigurable dipole antenna is presented as a proof-of-concept device, combining the properties of discretized metallic pixels, with the self-merging capabilities of liquid metal. The radiating elements of the antenna can be physically lengthened or shortened by merging or unmerging discrete volumes of liquid metal, which collectively form each of the two arms comprising a dipole antenna. This approach differs from a similar study [42] in which liquid-metal pixels are turned off by moving them to an electrically isolated ‘off’ storage reservoir, only to be turned back on by returning them to an electrically connected ‘on’ reservoir. Both studies offer alternative solutions which accomplish the same design objective: a dipole capable of frequency reconfigurability without the use of conventional RF switches, eliminating the insertion loss associated with them, and thus offering a scalable solution.

4.2 Design and Fabrication

Figure 4.1 illustrates the concept. The antenna is composed of a series of liquid-metal reservoirs, referred to as nodes, that are connected by channels. These liquid-metal nodes form the

conductive components of the dipole antenna. A gas-permeable silicone elastomer known as polydimethylsiloxane (PDMS) is used for the walls and ceiling of the nodes and channels, and glass is used for the covering. Each channel is $1 \text{ mm} \times 1 \text{ mm} \times 250 \text{ }\mu\text{m}$ and each node is $3 \text{ mm} \times 3 \text{ mm} \times 500 \text{ }\mu\text{m}$. The node dimensions are less than $\lambda_0/10$ for the operating frequencies of this antenna; previous MEMS-based approaches found these dimensions sufficient for reconfigurability [39], [40]. The antenna is probe-fed using a $50\text{-}\Omega$ SMA connector, modified with a soldered ground-pin extension. The SMA is electrically connected to the encapsulated liquid metal by two vias punctured through the PDMS and sealed with epoxy. The liquid metal used is Galinstan, a gallium-based alloy which remains liquid between $-19 \text{ }^\circ\text{C}$ and $1300 \text{ }^\circ\text{C}$ while maintaining an electrical conductivity of $2.30 \times 10^6 \text{ S/m}$ [10]. Galinstan is non-toxic and commercially available. An electrolytic solution (1 M NaOH) is also encapsulated in the channels, and removes the surface oxide inherent to gallium-based alloys [16]. The fabricated antenna is shown in Fig. 4.2.

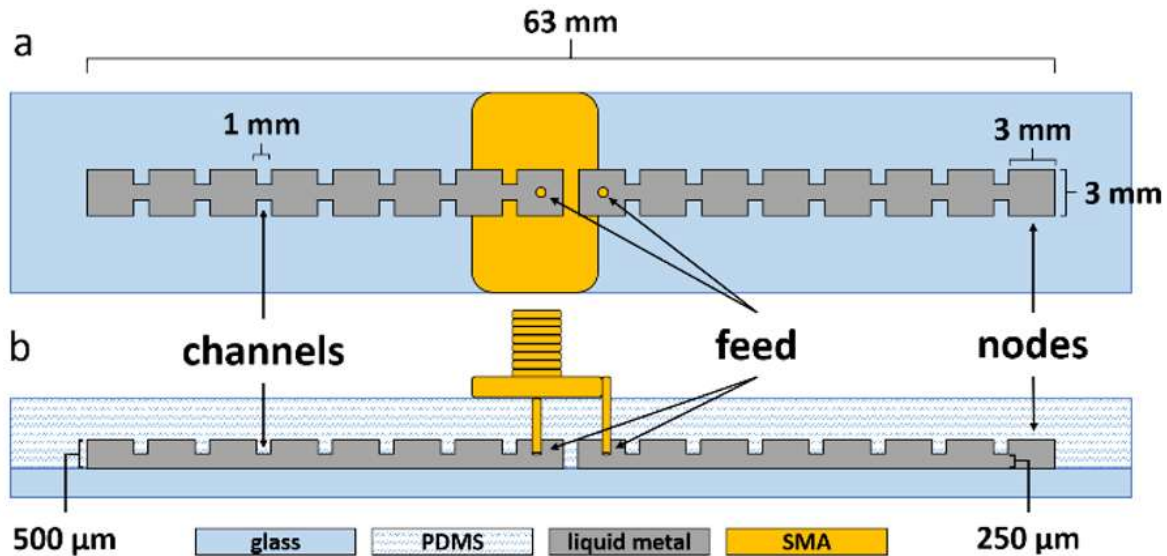


Figure 4.1: Illustration of antenna geometry: (a) top view; (b) cross-sectional view.

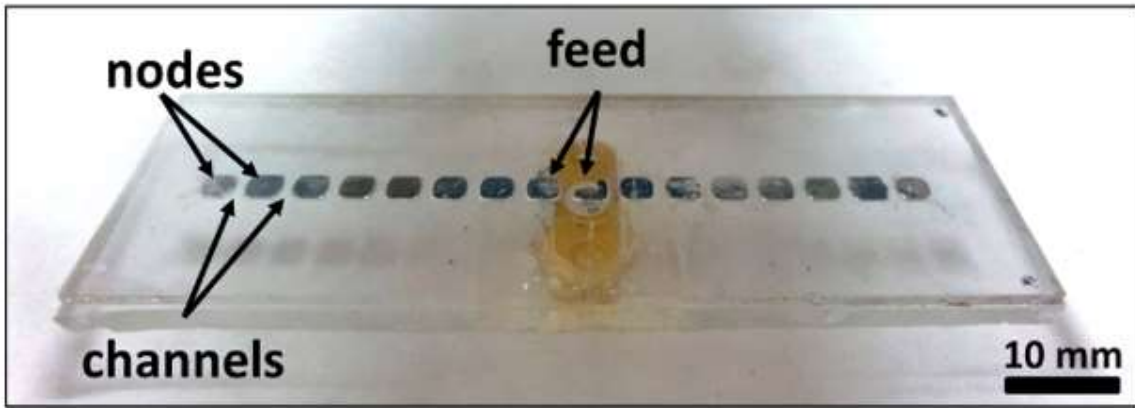


Figure 4.2: Fabricated liquid-metal nodal dipole antenna.

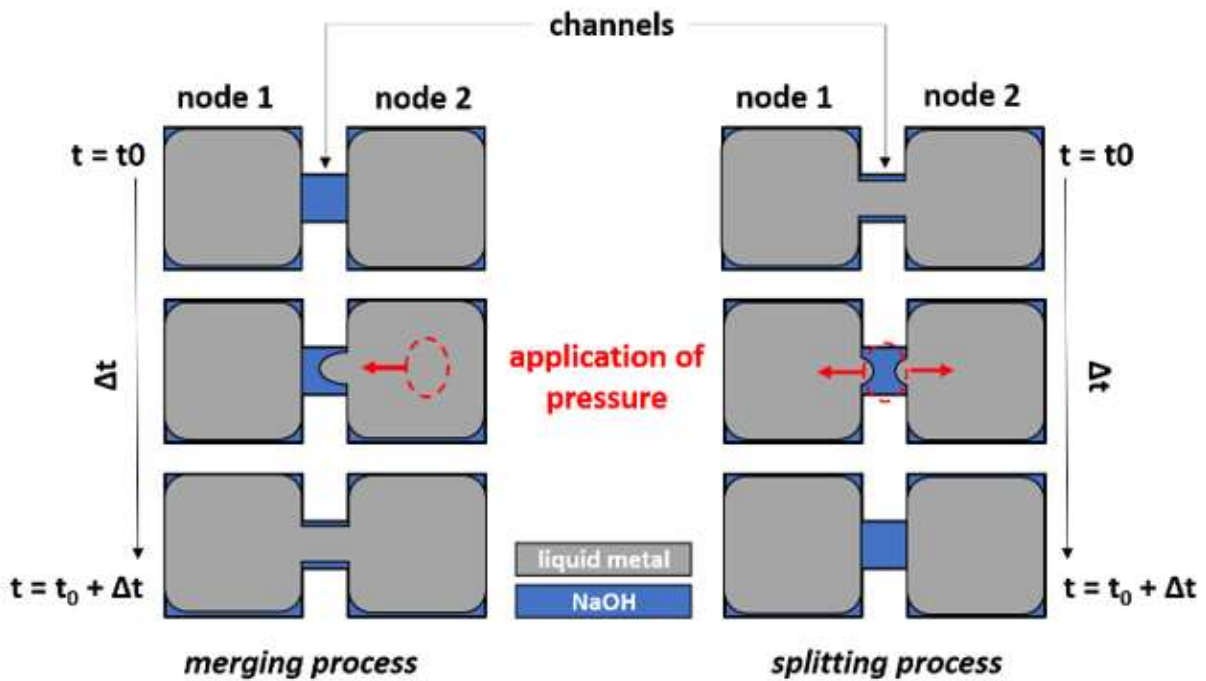


Figure 4.3: Pressure-point actuation: merging Nodes 1 and 2 by applying pressure to Node 2, forcing liquid metal into the connecting channel and merging the two nodes into a singular, multi-node element (left); splitting the singular, multi-node element composed of Node 1 and 2 into their discrete and unmerged state (right).

4.3 Pressure-Point Actuation

Reconfigurability is achieved by manually applying light pressure with the blunt end of a tweezer to merge or split nodes. The processes for merging and splitting are illustrated in Fig. 4.3. To merge adjacent Nodes 1 and 2, pressure is applied to Node 2, forcing liquid metal into the connecting channel and merging the two nodes into a singular, multi-node element. To split the merged Nodes 1 and 2, pressure is applied at the center of the connecting channel.

4.4 Antenna Operational States

Each connecting channel can be independently manipulated, allowing adjacent nodes to be merged or split in any combination. While this allows for a high degree of reconfigurability, only eight of these combinations form a dipole antenna structure of equal-arm lengths and are thus referred to as operational states. These states are illustrated in Fig. 4.4.

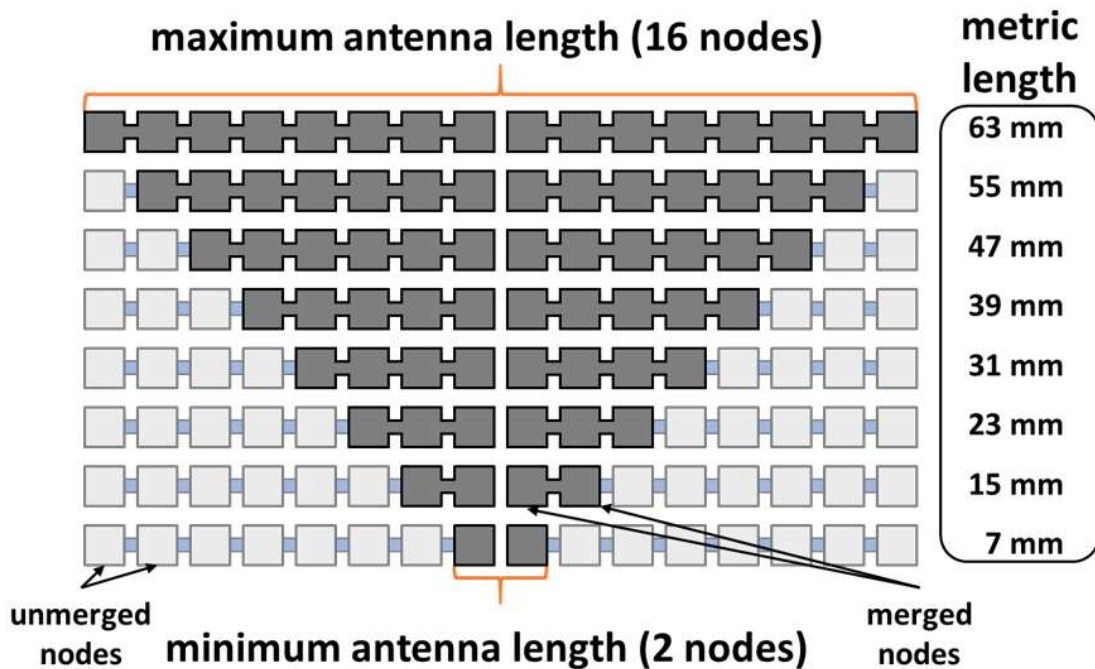
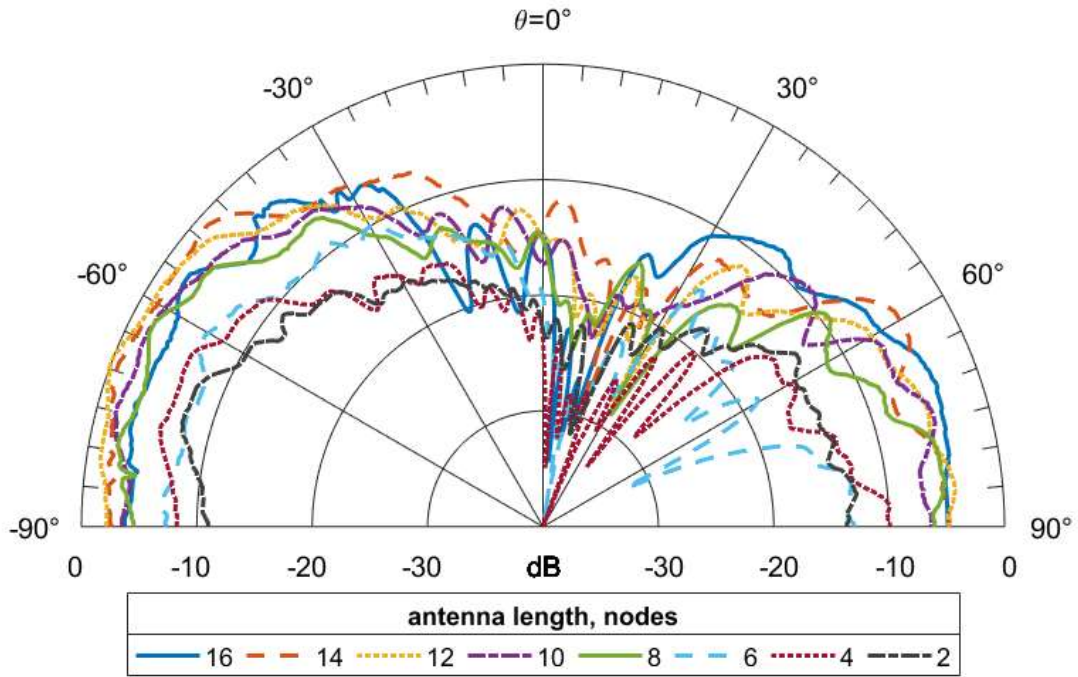


Figure 4.4: Illustration of antenna's eight operational states.

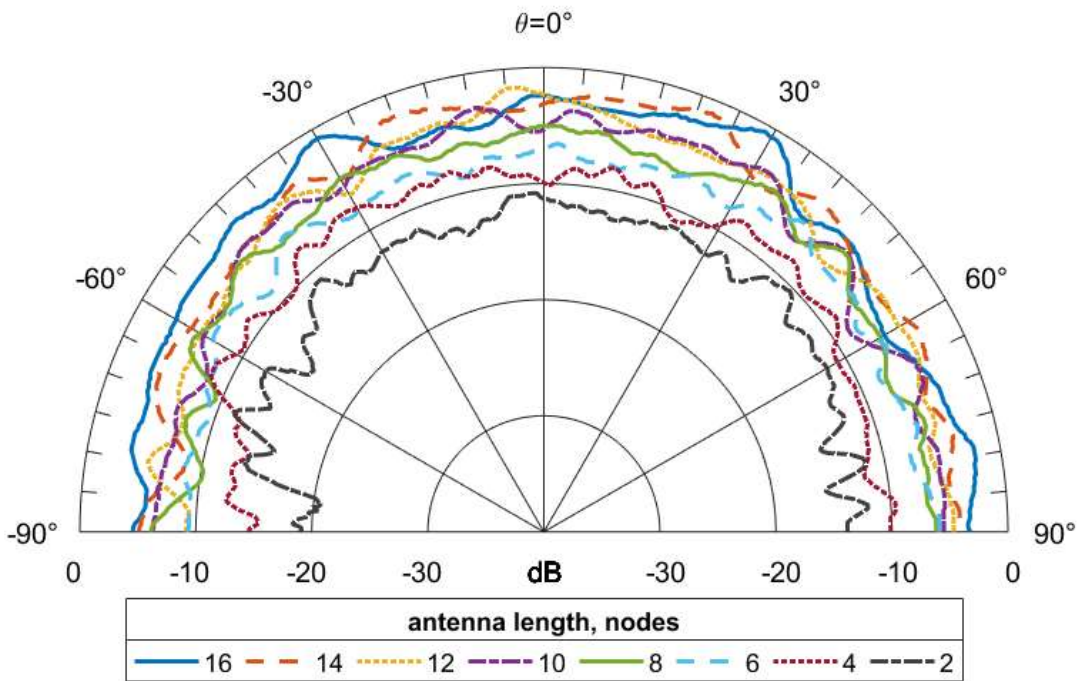
4.5 Experimental Results

The fabricated antenna was tested at each of the eight states. To achieve each state, the antenna was lengthened or shortened using the pressure-point actuation method to form a dipole antenna with a total physical length ranging from a minimum of 2 nodes (7 mm) to a maximum of 16 nodes (63 mm).

These varying antenna lengths correspond to a measured tunable bandwidth ranging from 1.59 GHz to 4.34 GHz with an average step-size of 395 MHz. Fig. 4.5 shows measured radiation patterns for the E-plane and H-plane cuts, which resemble that of a traditional dipole antenna. Discrete values for length, resonant frequency, and average gain for each state are given in Table 1. Average gain is highest (1.1 dBi) at the lowest frequency (1.59 GHz, where antenna length = 16 nodes) and lowest (-8.4 dBi) at its highest frequency (4.34 GHz, where antenna length = 2 nodes). The radiation patterns exhibit the traditional characteristics of a dipole antenna: E-plane with nulls at $\Theta = 0^\circ$ and an omni-directional H-plane. Although not plotted, the average cross-polarization ratio is 13.58 dB.



(a)



(b)

Figure 4.5: Measured radiation patterns for all operational states: (a) E-plane; (b) H-plane.

Length [nodes]	Frequency [GHz]	Average Gain [dBi]
16	1.59	1.09
14	1.75	0.54
12	1.96	-0.43
10	2.14	-0.92
8	2.51	-1.83
6	3.01	-2.97
4	3.44	-5.28
2	4.34	-8.40

Table 4.1: Length, frequency, and boresight gain for all operational states.

4.6 Conclusion

This chapter demonstrated a liquid-metal nodal dipole antenna with a frequency tuning range from 1.59 GHz to 4.34 GHz. Future work on the antenna will involve replacing the pressure-point actuation method with existing electrical actuation techniques of liquid metal.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

In this work, two actuation methods for manipulating liquid have been presented and demonstrated in functional RF devices. Broadly, this research was motivated by an immediate and universal need for innovative solutions broadening EMS spectrum sharing possibilities and communication capabilities. Specifically, this research was intended to improve the capability, diversity, and performance of actuation methods designed for reconfigurable liquid-metal circuits for RF applications.

In Chapter 2, the first actuation method, ferrofluidic actuation, improves upon existing actuation methods by using magnetic fields in combination with ferrofluid, simplifying fluidic channel design and reducing RF losses inherent to comparable electrical and magnetic actuation methods. In Chapter 3, ferrofluidic actuation is then used as the functional mechanism for an RF switch. The second actuation method presented, pressure-point actuation, is shown to be a simple technique in reconfiguring a planar radiating conductor by merging and splitting liquid metal nodes. A frequency-reconfigurable dipole is presented and illustrates its use in one application.

5.2 Future Work

A. Standing Issues

Two primary issues stand in conflict with the ultimate goals of this work. The first is achieving a reliable method of detecting liquid metal within a channel. Hydrocarbon-based ferrofluids, by nature, are opaque and require only a thin film of fluid to completely obstruct any passage of light (visible, infrared, or otherwise to the best of our knowledge). This is problematic, especially in a closed channel such as in Chapter 2, due to the effects of the slip layer. At lower velocities, the majority of ferrofluid comprising the slip layer has time to be displaced from between the glass and liquid metal as the liquid-metal slug is moved through a channel. This allows liquid metal to clearly be seen through the walls of a glass channel. At higher velocities (upwards of 50 mm/s) the slip layer does not have time to displace, creating a thicker film of ferrofluid between the liquid-metal slug and the glass wall of the channel. Consequently, visual detection is inadequate in characterizing ferrofluidic actuation at higher velocities. This phenomena is observed in Fig. 2.2 and illustrated in Fig. 5.1. DC resistance and AC impedance detection is our current course of research to address this issue. This phenomena is observed in Fig. 2.2

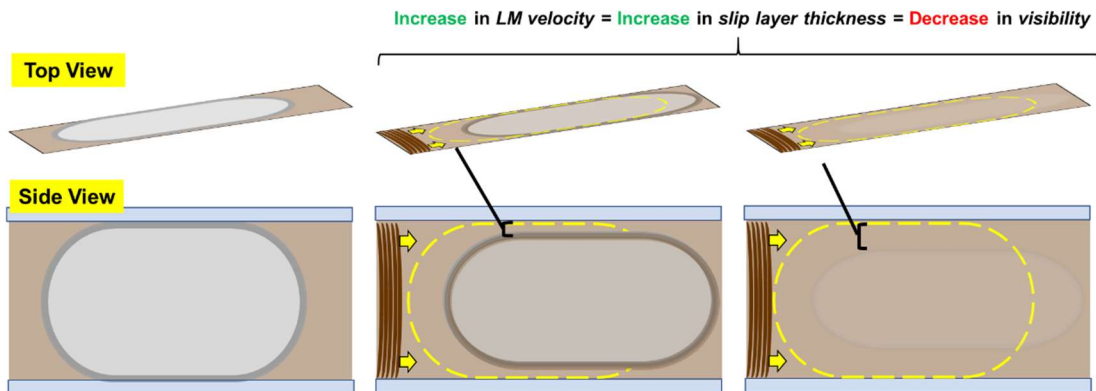


Figure 5.1: Ferrofluid slip layer causes difficulties in visually detecting liquid metal; (left) liquid metal displaces majority of ferrofluid slip layer and can be clearly through transparent channel walls, such as glass; (center) as liquid metal is moved with increasing velocity, the ferrofluid slip layer thickens, reducing visibility of liquid metal; (right) at higher velocities (upwards of 50 mm/s) the ferrofluid slip layer thickens enough for liquid metal to become visually imperceptible within the channel.

The second primary standing issue is that liquid metal becomes resistant to merging with itself when immersed in ferrofluid. This is likely a result of the surfactant coating used to prevent particle clumping in ferrofluids. It is evident a chemical reaction not fully understood is occurring between the surface of the liquid metal and the ferrofluid. Presumably, this is caused by the surfactant coating used in ferrofluid synthesis. As mentioned in Chapters 2 and 3, the particles are coated in a surfactant which prevents them from agglomerating in the carrier fluid (Fig. 5.2, top right). When liquid metal is exposed to ferrofluid, it is believed that the particles adhere to oxide skin of which forms on the surface of liquid metal. Because the sole purpose of the surfactant coating is to prevent agglomeration, it is believed the oxide-skin-fused-particles collectively form a surfactant coating, completely enveloping the liquid metal and reduce its ability to re-merge with other volumes of liquid metal. Further investigation into the causes of this could lead to greater structural integrity of the liquid-metal slug, and/or and a reliable method of splitting and merging liquid metal using ferrofluidic actuation.

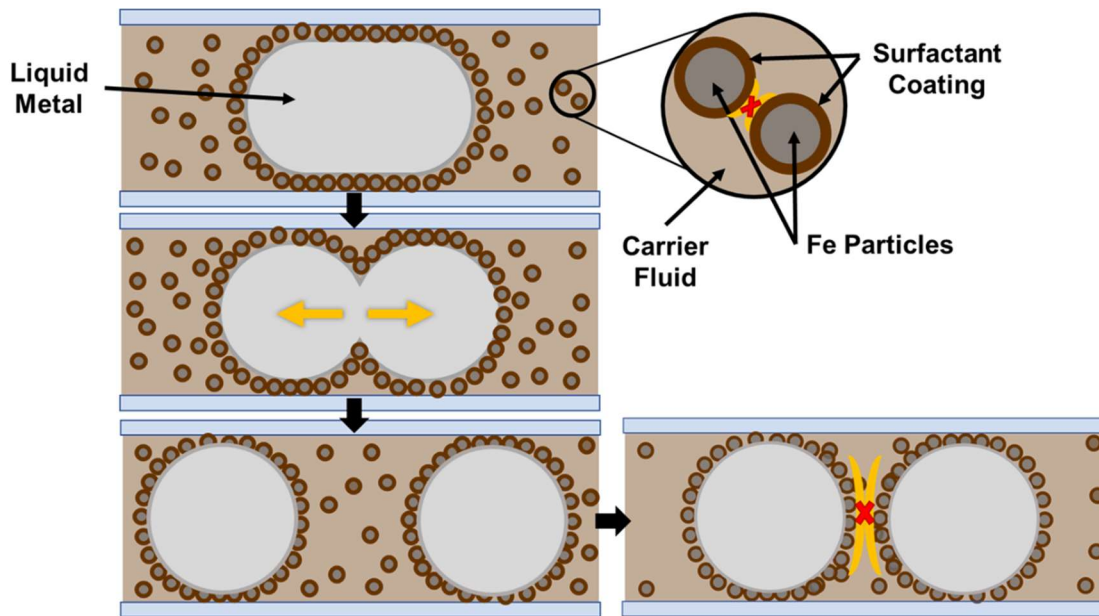


Figure 5.2: Liquid metal is resistant to re-merging with itself when immersed in ferrofluid

B. Characterization of Ferrofluidic Actuation

In order to set guidelines for future works using ferrofluidic actuation, an in-depth characterization of the technique is necessary for optimized designs. This includes determining the influence of channel design variables (e.g. channel aspect ratio, volume of liquid metal, magnetic field strength, percentage of channel filled with ferrofluid, angle of channel inclination, etc.) on the velocity and delay time of the liquid metal being moved. Positioning accuracy and reliability are also factors which must be addressed. In addition to channel design optimization, additional capabilities using ferrofluidic actuation are likely yet to be explored given the versatility of liquids and the unique properties magnetic forces possess, such as the allowance for sustained levitation of a magnetically-responsive material requiring no power consumption.

C. Ferrofluidic Actuation using Electro- and Electropermanent Magnets

Ultimately, we would like to enable electrically driven ferrofluidic actuation using electromagnets, electropermanent magnets [24], [43], or a combination of the two. This would be in lieu of rare-earth permanent magnets such as the neodymium ring magnet used in [33] and [44]. While permanent magnets have considerably stronger magnetic fields than electromagnets, using them is impractical because they must be manually repositioned (i.e. moved by hand) or mechanically driven, increasing power requirements, form factor, number of moving parts, and potential for failure. Electromagnets and lesser-known electropermanent magnets each have their pros and cons as well. Electromagnets are electrically driven, have tunable magnetic field strengths, and are widely commercially available, but they have the weakest magnetic fields of the three magnet types and require constant power to remain on. Electropermanent magnets are also electrically driven and require just one electrical pulse (124 W for the design in [24]) to switch from the OFF to ON state, and vice versa. Once switched, the magnetic field remains static, acting as a permanent

magnet with comparable field strength, until it is pulsed again to be turned OFF. However, the trade-off is these magnets are not widely commercially available, the magnetic field is not variable, and requires a relatively significant amount of power to switch states.

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