Liquid-Metal-Based Reconfigurable Components for RF Front Ends

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To my father for his hard-earned wisdom

To my mother for her unconditional love

To my brother for his unwavering courage

To my sister for her inspiring kindness

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I feel that this is a rare opportunity for me to share a bit of candidness and hope to make the most of it. I truly owe the completion of this thesis to many friends and family members and am sorry that I cannot thank you all.

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Abstract

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This thesis focuses on the development of liquid-metal-based reconfigurable components for radio-frequency (RF) front ends. Reconfigurable components allow the RF front end to dynamically change key radio parameters such as output power, signal carrier frequency, and bandwidth. These capabilities enable the radio transceiver to adapt to environmental and communication channel changes on the fly, according to programmed protocols and priorities. As a low-loss metallic conductor, the liquid metal Galinstan is well suited for RF applications, and its fluidic nature makes it a natural candidate for reconfigurable architectures. Three liquid-metal based components are described: a frequency-tunable substrate integrated waveguide cavity filter, an electromagnetic bandgap phase shifter, and a frequency-reconfigurable slot antenna. These components are designed, fabricated, and tested and the advantages and disadvantages of using liquid metal are discussed.

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Chapter 1

Introduction

Telecommunications, whether through wired connections or wireless waves, has become a fundamental part of modern society [1]. The emergence of the internet and mobile wireless communication systems in recent decades has been a critical enabler for economic growth, social networking, media consumption, and information sharing.

Figure 1.1: Number of mobile-cellular subscriptions worldwide [1].

Figure 1.2: Number of smartphone, tablet, mobile PC, and mobile router subscriptions [1].

There are currently over 6.7 billion mobile-cellular subscriptions worldwide as shown in Fig. 1.1. Of those mobile-cellular subscriptions as many as 3.3 billion are smartphone subscriptions, a number expected to grow to over 5.6 billion by 2019 (Fig. 1.2). These graphs show that an increasing amount of consumers are using mobile phones as well as migrating toward faster wireless communication technologies. This demand for faster speeds comes in conjunction with an expectation of an acceptable quality of service and availability.

Much of the success of mobile phones can be attributed to recent developments in integrated circuits, software architectures, and signal-processing algorithms. 4G Long-Term Evolution (LTE) is the first global mobile broadband standard and has now been deployed by many cellular companies to increase the capacity and speed as well as decrease the latency of wireless communications for mobile phones [4]. However, LTE is incompatible with 2G (GSM, CDMA) and 3G (HSPA, CDMA2000) networks, thus LTE must be operated on a different part of the wireless spectrum. Furthermore, LTE is operated across multiple

different frequency bands within a single service provider. These frequency bands also differ from those used by other service providers, which also differs between countries [5]. Modern mobile phones must not only be LTE capable, but also be able to operate with previous 2G and 3G cellular networks as well with other forms of wireless communications such as Wi-Fi, Bluetooth, Global Positioning System (GPS), and Near Field Communication (NFC). Efficient operation across these different technologies of wireless communications has brought increased pressure on improving the RF front end of mobile phones.

1.1 RF Front End Background

Figure 1.3: Block diagram of a RF front end.

The RF front end is a subsystem within the radio transceiver that is responsible for the reception and transmission of the wireless signals. On the receive side of the RF front end, the subsystem typically consists of an antenna to convert electromagnetic waves into alternating currents, a filter to isolate the communication band of interest, a low-noise amplifier (LNA) to boost the filtered signal to detectable levels, and impedance-

matching networks at the amplifier input and output to optimize its performance for noise and gain. Virtually all modern radio transceivers then use the superheterodyne architecture to downconvert the incoming RF signal into a lower intermediate frequency (IF) that is easier to demodulate and process by the rest of the transceiver. The downconversion is accomplished by mixing the incoming signal with that from a local oscillator (LO). On the signal transmission side, the RF front end receives a data-encoded modulated signal from the rest of the transceiver. This signal is then upconverted to the transmission frequency by a similar mixing process, amplified with a power amplifier (PA), filtered, and lastly converted into electromagnetic waves into the air by the same antenna used for signal reception (Fig. 1.3). A switch is used to determine whether the RF front end is receiving or transmitting signals.

Conventional multi-band radio transceivers use static components designed for a single frequency band of interest, requiring typically one amplifier and filter each per band [6]. To minimize the antenna volume in the mobile phone, the number of antennas is not multiplied to the same degree in modern transceivers [7]. Instead the antenna is designed to be multi-band to capture all of the frequencies of interest [7]. The switch then feeds from the antenna, with outputs to each of the transmission and reception chains. This architecture contains redundancies and is not scalable to dozens of bands [6], because of the added complexity, costs, and board space required for each additional chain in the RF front end.

This thesis proposes a technique for reconfiguring components in the RF front end to reduce complexity, cost, and size. Instead of having components that are static and

designed to work at one particular frequency, the components can be made reconfigurable to be tuned to work at different frequencies on the fly. Although a single tunable component can be more complex than its respective static component, a chain of tunable components can reduce the need for multiple chains of static components to have a net benefit to the RF front end.

This architecture of reconfigurable RF components can enable future radio transceivers the capability to dynamically adapt to changing conditions, resulting in wireless systems that are more versatile, multifunctional, robust, and economical. This aligns with the White House directive identifying broadband wireless networks as one of our nation's key economic drivers, and its push to make more efficient use of the radio spectrum to enable more users to share an already overly crowded natural resource [8].

1.2 Reconfigurable Technology Survey

The idea of reconfigurability is certainly not a new one and has been implemented in various ways. A common technique to tune the performance of a device is to use a switch to turn on and off constituent elements of the device. For example, switches are commonly used to reconfigure current paths in an antenna to enable frequency tuning [9]. An ideal switch would have low insertion loss, high isolation, high linearity, high power handling, and a fast switching speed, all while consuming no power and fitting within a small form factor [10]. Currently, no existing technology meets all of these criteria, but oftentimes the application allows for concessions to be made in some of these switch characteristics, while prioritizing others. Contemporary techniques involve the use of variable

reactive components such as PIN diodes, field-effect transistors (FETs), and variable capacitors (i.e. varactors). PIN diodes and FETs can be modeled as a small resistive element in the on state and a low capacitive element in the off state [11]. These components are attractive for their small size, low cost, and low power consumption, however due to their semiconductive qualities, additional losses and nonlinear distortion are introduced. Electromechanical relays operate much closer to an ideal switch by physically connecting or disconnecting a conductive path, but their applications in RF devices are limited due to their large size, high cost, and relatively low lifetime of switching cycles [10]. In recent decades, microelectromechanical systems (MEMS) have been developed to be an effective alternative technology. MEMS switches can be thought of as miniaturized electromechanical relays that operate based upon forces which are more prominent at smaller scales, such as electrostatic, piezoelectric, magnetostatic, and thermal forces. However, MEMS technology can often require high actuation voltages and strict packaging conditions [10].

1.3 Liquid Metal Overview

An alternative, radical paradigm shift from these techniques is to use liquid metal as a tuning mechanism to create dynamic circuit elements with conformable shape and size. It could then be possible to create reconfigurable circuits reminiscent of the shape-shifting cyborg from the movie *Terminator 2*. The most commonly known liquid metal at room temperature is mercury, but its most serious drawback is its high toxicity. An attractive alternative is a nontoxic liquid metal with the trade name of Galinstan[™] (Fig. 1.4), a eutectic alloy consisting of approximately 68.5% gallium, 21.5% indium, and 10% tin (% by weight).

Figure 1.4: A droplet of Galinstan liquid metal.

Galinstan has an electrical conductivity of 2.3×10^6 S/m, and retains its liquid state from -19 to 1300° C. The properties of Galinstan compare well to other commonly used liquid metals, such as mercury, EGaIn (75% Ga and 25% In by weight), pure gallium, and solid copper as shown in Table 1.1. All of the work presented in this thesis uses Galinstan.

Table 1.1: Properties of copper compared to room-temperature liquid metals

Metal	Melting point [$^\circ$ C]	Boiling point [$^\circ$ C]	Electrical conductivity [S/m]	Thermal conductivity [W/(m·K)]	Toxicity
Copper	1083	2595	5.8×10^7	398	Low
Mercury	-38.87	356.73	1.04×10^6	11.69	High
Galinstan [12]	-19	1300	3.14×10^6	25.41	Low
EGaIn [12]	15.7	-	3.28×10^6	26.43	Low
Gallium [12]	29.8	2403	3.82×10^6	30.54	Low

1.3.1 Relevant Fluid Mechanics

This subsection provides a brief overview of relevant fluid mechanics and liquid properties, which can be taken advantage of when designing fluidic channels to achieve a desired fluid flow.

Galinstan can be modeled as an incompressible liquid. Although all fluids are susceptible to changes in density due to changes in pressure and temperature, these changes generally must be very large to incur an appreciable change in density. Thus liquids can be modeled with incompressible flow, which makes their motion easier to predict when pressure is applied [13]. In contrast, a compressible fluid such as air would have a dampened effect when pressure is applied to it.

Liquids also exhibit a cohesive force known as surface tension. Galinstan has a surface tension of 534.6 ± 10.7 mN/m [14], which is very high compared to that of water which is 72.75 mN/m. Surface tension is analogous to surface energy and is the cause for the innate ability of liquids to minimize their surface area. This is a result of the liquid having a greater attraction to its own molecules than to the molecules in its surrounding medium. The molecules within the bulk of the liquid are equally attracted to its surrounding neighbors, but the molecules on the surface of the droplet have a net pull inward. Thus in the absence of other forces, liquids would form into a sphere, but in reality often tend to form droplets or beads on most surfaces. This concept of surface energy is important when designing fluidic channels as the liquid will naturally prefer large open areas of the channel over narrow small ones.

When a liquid droplet comes into contact with a surface, its wettability is quanti-

Figure 1.5: A liquid droplet on a (a) hydrophilic surface and (b) hydrophobic surface.

defined by the contact angle θ_c between the interface of the liquid and surface (Fig. 1.5). The term wettability describes how well the liquid adheres to a surface. Surfaces with contact angles smaller than 90° are hydrophilic and are considered wetting (Fig. 1.5.a), while contact angles larger than 90° are considered hydrophobic and nonwetting (Fig. 1.5.b). For fluidic channels, this concept can be used to attract liquids in a desired direction with hydrophilic surfaces or repelled with hydrophobic surfaces.

All of the previous concepts can be taken advantage to design fluidic channels to achieve a predictable flow of liquid metal when it is uncontaminated. However, an issue of working with Galinstan and other gallium-based alloys is that they develop an oxide film almost instantly in the presence of oxygen in concentrations as low as 1 ppm [14]. This layer of oxide causes the liquid metal to behave more like a gel than like a common liquid. In this oxidized state, Galinstan will wet to many materials it otherwise would not wet to, which causes it to adhere to channel walls preventing motion. The development of this oxide layer can be prevented through the use of nitrogen boxes and hermetic sealing, however both are costly and time consuming. An alternative is to use a strong acidic or basic solution to

chemically reduce the oxide layer [2].

1.4 Thesis Organization

The objective of this thesis is to develop the use of nontoxic liquid metal as a dynamic element to create reconfigurable components for RF front ends. Chapter 2 presents the design, fabrication, and measurement of a frequency-tunable substrate integrated waveguide cavity filter with liquid-metal perturbing posts. Chapter 3 explores the use of liquid metal to switch on and off electromagnetic bandgap structures to create a phase shifter. In Chapter 4, the concept of actuating liquid metal through pressure-driven air bubbles is explored and used to create a frequency-reconfigurable slot antenna. The conclusions of this research are presented in Chapter 5, as well as suggestions for future work, other liquid-metal actuation techniques, and concerns for commercialization and miniaturization.

Chapter 2

A Tunable X-Band Substrate

Integrated Waveguide Cavity

Filter using Reconfigurable

Liquid-Metal Perturbing Posts ¹

The previous chapter introduced the RF front-end subsystem and the concept of reconfigurability with different technologies. This chapter presents a frequency-tunable filter that reduces the number of required filters, thus saving board space and potentially scaling down the number of front-end modules required when combined with other reconfigurable components. The filter is constructed using the substrate integrated waveguide (SIW) architecture and is made reconfigurable using liquid-metal perturbing posts. Comparisons to

¹The work presented in this chapter is an expansion of [15]

other reconfigurable SIW filters based upon different techniques are made. This is believed to be the first instance of liquid metal being used to create a tunable SIW filter [15].

2.1 Introduction

As the need for greater bandwidth and faster data rates continues to push communication systems into the millimeter-wave band [16], SIW technology has garnered increased attention from researchers. At these frequencies conventional microstrip can suffer from higher insertion loss [17], giving them a quality (Q) factor too low for many applications. Metallic waveguides have high- Q transmission characteristics, but are also bulky, expensive, and difficult to integrate with planar structures. SIW represents a compromise technology, combining the low loss, high- Q advantages of metallic waveguides while maintaining a PCB manufacturing-compatible structure for ease of integration as well as reduced cost and size.

SIW techniques can be leveraged to create precision band-pass filters with much higher Q -factors than comparable planar filters [18, 19]. The performance of these filters is often based on the location of metallic posts [20], and while the post locations are fixed, the filters themselves can be made tunable by using variable reactive components such as varactors [21] and PIN diodes [22]. However, the parasitics associated with these semiconductor elements can limit the tuning bandwidth of these filters and contribute to insertion loss. Microelectromechanical systems (MEMS) switches have also been used effectively [23], but this technology can involve high actuation voltages and strict packaging requirements.

Here, we propose the use of a nontoxic liquid metal alloy Galinstan [14]) to create a tunable SIW bandpass filter. As a low-loss metallic conductor, Galinstan is well

suited for high-Q applications [24], and its fluidic nature makes it a natural candidate for reconfigurable devices, including tunable antennas [25], planar filters [26], and baluns [27].

2.2 Tunable SIW Filter Design

2.2.1 SIW Cavity Theory

Figure 2.1: Layout of the prototype SIW filter top view (bottom is fully cladded with copper, except at the four white vias).

The SIW bandpass filter is based on the physical dimensions of the cavity, which is determined by the placement of via posts using [28]:

$$f_{101} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{\pi}{w_{eff}}\right)^2 + \left(\frac{\pi}{l_{eff}}\right)^2}, \quad (2.1)$$

where f_{101} is the first resonant frequency, c is the speed of light, μ_r is the relative permeability, ϵ_r is the relative permittivity, w_{eff} is the effective width, and l_{eff} is the effective length of the cavity. The effective width and length of the cavity can be calculated from [28]:

$$w_{eff} = w - \frac{d^2}{0.95p}, \quad l_{eff} = l - \frac{d^2}{0.95p}, \quad (2.2)$$

where w is the width, l is the length, d is the diameter of the posts, and p is the pitch (i.e. spacing between the posts). Each dimension is measured using the center-to-center distance of the posts as indicated in Fig. 2.1.

To minimize radiative losses two design rules for the diameter and pitch of the posts are [29]:

$$d < \frac{\lambda_g}{5}, \quad p \leq 2d, \quad (2.3)$$

where λ_g is the guided wavelength.

2.2.2 Liquid-Metal Perturbing Posts

Figure 2.2: Cross section of the SIW filter.

To enable reconfigurability, tunable perturbing posts within the cavity of the SIW have been demonstrated with the use of varactors [21], PIN diodes [22], and MEMS switches [23]. These techniques add complexity and parasitics to the structure with the additional bias, control lines, and floating via posts [21–23]. In contrast, the design described here has perturbing posts that consist simply of a hollow via that can be either filled with liquid metal or evacuated with the use of a pump. The additional power consumption and bulk of the pump is a design tradeoff for reduced parasitics.

2.2.3 Fabrication

Figure 2.3: Fabricated liquid-metal SIW filter with vias A and C filled with liquid metal and vias B and D unfilled. Ports 1 and 2 are SMA connectors soldered to 50- Ω microstrip lines.

The SIW filter is implemented on Rogers Duroid 5880 substrate with a thickness of 0.79 mm and $\epsilon_r = 2.2$. The cavity dimensions are $w = 13.5$ mm and $l = 13.75$ mm as shown in Fig. 2.1. The SIW cavity posts have dimensions $d = 0.8$ mm and $p = 1.25$ mm. From (2.1) and (2.2), the unperturbed resonant frequency of the cavity is approximately 10.93 GHz. At each corner of the cavity, 2.5 mm away from each rail of posts, a 0.8-mm-diameter hollow via is drilled. Plastic channels are fabricated over these hollow vias on both the conductor and ground plane to contain the liquid metal, as shown in Fig. 2.2. The channel consists of a 0.6-mm thick polyimide wall and a 0.4-mm thick polyvinyl chloride (PVC) ceiling. Injection points are then drilled into the PVC ceilings. These vias can be filled with liquid metal to perturb the cavity, or evacuated to reverse the perturbation.

2.3 Experimental Results

The fabricated SIW filter is shown in Fig. 2.3. There are four hollow vias that can be independently filled or evacuated with liquid metal, which are labeled A, B, C, and D.

Each via is controlled with a 1-mL syringe. After evacuating the liquid metal from the via, the channel is flushed with a 1% solution of NaOH to remove any residual oxidized liquid metal [2]. This step is necessary as the liquid-metal Galinstan oxidizes in concentrations of oxygen as low as 1 ppm [14].

The SIW filter initially starts in State 1 with each via empty. As each via is filled to create a new perturbing post, the resonant frequency of the SIW cavity is progressively increased until reaching its highest frequency in State 5 with all of the vias filled. The measured and simulated S_{21} (Fig. 2.4) and S_{11} (Fig. 2.5) show good correlation. The simulated data was created from Keysight Advanced Design System (ADS) finite-element method full 3D electromagnetic simulator.

Figure 2.4: Measured and simulated S_{21} as the SIW filter is reconfigured into States 1 to 5.

Table 2.1 summarizes the measurements at each filter state with the locations of the perturbing posts. The unloaded Q -factor can be calculated from [11]:

$$Q_L = \frac{f_o}{\Delta f_{-3dB}}, \quad Q_U = \frac{Q_L}{1 - S_{21}(f_o)}, \quad (2.4)$$

where Q_L is the loaded Q -factor, Q_U is the unloaded Q -factor, f_o is the center resonant

Figure 2.5: Measured and simulated S_{11} as the SIW filter is reconfigured into States 1 to 5.

Table 2.1: Liquid-metal SIW filter state summary

State	0 - via evacuated, 1 - via filled				
	Via (ABCD)	f_o [GHz]	Peak S_{21} [dB]	FBW [%]	Q_U
1	0 0 0 0	10.13	-0.93	0.80	154
2	0 0 1 0	10.41	-1.20	0.94	132
3	1 0 1 0	10.70	-1.35	0.76	112
4	1 0 1 1	10.99	-1.54	1.03	108
5	1 1 1 1	11.31	-1.74	0.57	96

frequency, and Δf_{-3dB} is the bandwidth for which the S_{21} is within 3 dB of the insertion loss at f_o .

The tunable bandpass filter demonstrates five reconfigurable states spanning 10.13 GHz to 11.31 GHz, with fractional bandwidths (FBW) ranging from 0.57% to 1.03%, for which the S_{11} is less than -10 dB. The average peak insertion loss of the device is approximately 1.35 dB, which includes the losses of the SMA connector and 7.5-mm microstrip line at each end of the device. Each liquid-metal post contributes to approximately 0.20 dB of insertion loss. These measurements were obtained with manual hydraulic actuation

with a syringe. A previously demonstrated micropump used for liquid-metal actuation has been shown to provide a maximum flow rate of 5 mL/min [30]. Thus for a hollow via with a volume of 0.4 μL , it can be filled or evacuated in approximately 5 ms.

Table 2.2 compares the performance of this filter to other frequency-reconfigurable SIW cavity filters using varactors, PIN diodes, and RF MEMS. The results of this filter show that a comparable Q_U is achieved with less insertion loss. The tuning bandwidth (TBW) of this device can be enlarged by moving the posts towards the center of the cavity to induce larger perturbations [22].

Table 2.2: Comparison of different frequency-reconfigurable SIW cavity filters

Filter & Year	Technology	Frequency range [GHz]	TBW [%]	Insertion loss [dB]	Q_U
This work [15]	Liquid metal	10.1 - 11.3	11	0.9 - 1.7	96 - 154
[21] 2011	Varactor	2.6 - 3.1	18	-	40 - 160
[22] 2010	PIN diode	1.55 - 2.0	25	3.8 - 5.4	101 - 120
[23] 2011	RF MEMS	1.2 - 1.6	28	2.2 - 4.1	93 - 132

2.4 Summary

This chapter demonstrated a tunable bandpass filter based on reconfigurable liquid-metal perturbing posts in an SIW cavity. Liquid metal is injected into hollow vias to create perturbations in the SIW cavity, which enable the cavity's resonant frequency to be tuned. This process can be reversed by evacuating the liquid metal. Five reconfigurable states are measured and simulated with good correlation. The measured states span 10.13 GHz to 11.31 GHz, with a FBW ranging from 0.57% to 1.03%, for which the S_{11} is less than -10 dB. The average peak insertion loss is 1.35 dB with Q_U -factors of up to 154. These results are

comparable to tunable SIW cavity filters implemented with varactors [21], PIN diodes [22], and MEMS switches [23].

Chapter 3

Liquid-Metal-Based Phase Shifter with Reconfigurable EBG Filling Factor ¹

The previous chapter demonstrated a reconfigurable SIW filter using liquid-metal perturbing posts. In this chapter, a phase shifter is implemented using an electromagnetic bandgap (EBG) structure. Phase shifters are used in the RF front end of phased array antenna systems for beamforming and beam steering [32]. They are also used in many other applications including phase discriminators, power dividers, and for the linearization of amplifiers. The presented phase shifter uses EBG elements with different filling factors (FF) to realize multiple gradations of phase shift. Liquid metal is then used to switch the EBG elements on and off.

¹The work presented in this chapter is an expansion of [31]

3.1 Introduction

The periodic nature of EBG structures not only results in a stopband, making them useful for filters, but also generates a slow-wave effect in the passband [33], which is useful for realizing phase shifters. For example, a phase-shifting network for beam steering was demonstrated using a microstrip line with a defected ground plane, whose delay was linearly proportional to the number of EBG elements [34]. This idea was extended in [35], where the phase shift was also shown to be linearly proportional to the EBG FF. Although both papers proposed using MEMS switches to enable reconfigurability, only fixed phase shifts were demonstrated.

This chapter demonstrates an EBG capable of dynamic phase shifting. The structure consists of a 1D periodic lattice of holes etched in the ground plane of a microstrip line (Fig. 3.1). In contrast to previously published EBGs of this type [36], this design incorporates two novel features: (1) multiple FFs to create gradations in the amount of phase shift, and (2) the use of liquid metal to reversibly fill in holes in the ground plane (turning an EBG element off) and vice versa, enabling reconfigurability.

Figure 3.1: Schematic of the EBG phase shifter, top view before channel fabrication.

3.2 Liquid-Metal Phase Shifter Design

3.2.1 EBG Phase Shifter Theory

The stopband center frequency of an EBG is related to its lattice period according to [37]:

$$f_{stop} = \frac{c}{2a\frac{\beta}{\beta_o}}, \quad (3.1)$$

where c is the speed of light in a vacuum, a is the EBG period, β is the propagation constant in the EBG structure, and β_o is the free-space propagation constant. The FF is the ratio r/a , where r is the radius of the circle. For a small FF, the stopband center frequency can be calculated using the propagation constant of the unperturbed microstrip line. Equation (3.1) can then be approximated to show that the period is roughly half of a guided wavelength at the stopband center frequency. As the FF increases, the stopband depth and width increase, but the passband ripple increases. An FF of 0.25 is an optimal balance for minimizing passband ripple and maximizing stopband depth [36].

3.2.2 Fabrication

The EBG phase shifter was implemented on the ground plane of a 50- Ω microstrip line (2.45 mm wide, 152 mm long). The substrate is Rogers Duroid 5880, which has a dielectric constant of 2.2 and a thickness of 0.79 mm. The unperturbed effective dielectric constant for a microstrip line on this substrate is approximately 1.87. Thus, for an EBG periodicity $a = 10.9$ mm, the stopband center frequency is approximately 10 GHz. Centered directly under the microstrip line, 12 circular voids are etched into the ground plane, and

repeat along the length of the line in a single row. This periodicity is kept constant between all EBG elements. To achieve multiple gradations of phase shifting, the 12 EBG elements are divided equally into three sections, each with a unique FF. The center section has the optimal $FF=0.25$, which corresponds to a radius of 2.7 mm. This radius is scaled up and down by a factor of 1.5 to result in radii of 4.05 ($FF=0.37$) and 1.8 mm ($FF=0.17$) for the adjacent sections. The slow-wave passband of the resulting device extends from DC to 6 GHz.

(a)

(b)

Figure 3.2: The fabricated EBG phase shifter (a) with liquid metal evacuated from the indicated outlets to reveal the EBG structures numbered 1 to 12 and (b) cross section of a channel with liquid metal.

The liquid metal is contained in elliptical microfluidic channels (Fig. 3.2.a). The channels consist of ovals (16.2 mm major axis, 10.1 mm minor axis) cut into a 0.6-mm-thick polyimide layer. The channels are enclosed by a 1-mm-thick polystyrene ceiling. A

cross-sectional view of the device and channels is shown in Fig. 3.2.b. Since Galinstan can readily bond to copper, and thus prevent reconfiguration, a 0.1-mm layer of polyimide floor beneath the channel isolates the liquid metal from the copper ground plane [38]. Inlets and outlets at the ends of each channel allow for syringes to pump the liquid metal. To turn off an EBG element, liquid metal is pumped in to fill the channel. The liquid metal can also be evacuated to turn the EBG element back on. A 1% solution of NaOH is used to reduce the oxide of Galinstan [39] and flush any residue when evacuating the channels. The channel is also lined with PTFE, which acts as a lubricant to facilitate pumping. The PTFE is applied using a solution of Duraglide.

3.3 Experimental Results

Each of the 12 EBG elements can be independently actuated on and off. To achieve a consistent linear phase shift, the periodicity must be maintained. Fig. 3.3 shows a representative set of 13 state measurements to demonstrate the linearity of the phase shift. The 12 channels are initially all filled with liquid metal, which switches the phase shifter to the all-off State (0000,0000,0000). The liquid metal is then evacuated element by element in ascending numerical order to switch them on, ending with State (1111,1111,1111). The phase lag of each state, normalized to the phase lag of the initial State (0000,0000,0000) was measured from 1 GHz to 6 GHz (Fig. 3.3.a). When all 12 EBG elements are in the on state (1111,1111,1111), the total phase shift is 7° at 1 GHz and 80° at 6 GHz; the measured 3-dB cutoff frequency of the passband is approximately 6 GHz. There is some nonlinearity at higher states because of the addition of larger perturbations, and there is an increase in

(a)

(b)

Figure 3.3: Phase lag normalized to State (0000,0000,0000) as liquid metal is evacuated to turn on the EBG elements from right to left, $FF=0.17 \rightarrow 0.25 \rightarrow 0.37$ (a) 1 GHz to 6 GHz and (b) at 5.6 GHz.

nonlinearity as the phase shifter operates closer to its 3-dB cutoff frequency.

The least-squares method is used to approximate the line of best fit for the phase lag with respect to the three EBG sections. Fig. 3.3.b shows the results at 5.6 GHz. The slope of each line approximates the relative increase in phase lag per respective EBG element, and the deviation from that line is defined here as the phase error. Table 3.1 summarizes both of these quantities corresponding to each FF. The results show that EBG

elements with larger FF contribute a larger phase lag.

Table 3.1: Filling factor vs. phase lag per EBG element at 5.6 GHz

Filling Factor	Average phase lag [degrees/EBG element]	Average phase error [degrees]
0.17	1.8	0.09
0.25	5.7	1.03
0.37	9.4	0.46

(a)

(b)

Figure 3.4: Measured (a) S_{21} and (b) S_{11} . Not all intermediary states are shown for clarity.

The measured S_{21} and S_{11} are shown in Fig. 3.4.a and Fig. 3.4.b respectively. Only

the bookend states for each FF are shown for clarity. The S_{11} is under -10 dB except for the last state in a few frequency ranges. The average insertion loss of the measured states at 5.6 GHz is 1.1 dB, or 0.29 dB per guided wavelength, with a worst-case total loss of 1.8 dB. A microstrip line with the same dimensions but with an unperturbed ground plane was fabricated for comparison and had an insertion loss of 0.6 dB, or 0.15 dB per guided wavelength, at 5.6 GHz. The additional losses of the phase shifter can be attributed to localized impedance mismatches and increased radiation losses caused by the EBG elements in the on state, and imperfect coupling between the liquid-metal slug and ground plane in the off state. A common figure of merit (FoM) for phase shifters is the degrees of phase shift per dB of insertion loss. The FoM of the presented phase shifter at 5.6 GHz is shown in Fig. 3.5. The best case FoM is approximately $70^\circ/\text{dB}$.

Figure 3.5: FoM at 5.6 GHz across the different states of the phase shifter.

3.4 Summary

A phase shifter with multiple gradations of phase shifting is realized through the integration of three EBG structures with FF of 0.17, 0.25, and 0.37. Liquid metal is used to switch the EBG elements on or off, enabling reconfigurable phase shifting. At 5.6 GHz, a relative phase shift of 1.8° , 5.7° , and 9.4° is achieved per EBG element, depending on its FF, resulting in a total phase shift of 0° to 67.2° in varying steps. The phase shifter has an average insertion loss of 1.1 dB at 5.6 GHz across the measured states.

Chapter 4

Liquid-Metal

Frequency-Reconfigurable Slot

Antenna Using Air-Bubble

Actuation ¹

The previous two chapters demonstrated liquid-metal components that used conventional hydraulic pressure to reconfigure their liquid-metal elements to induce performance changes. This required the use of a 1% NaOH solution to rinse the liquid metal to remove any metal oxidation and therefore be able to cleanly evacuate the liquid metal. In contrast, this section presents the reversible and repeatable actuation of liquid metal via pressure-driven air bubbles. This technique is demonstrated to dynamically reconfigure

¹The work presented in this chapter is an expansion of [40]

the length of the feed line and radiating aperture of a slot antenna to enable frequency-reconfigurability.

4.1 Introduction

Reconfigurable antennas have become increasingly attractive as a means of efficiently mitigating spectrum congestion in wireless communication systems. In contrast to static antennas, reconfigurable antennas are capable of dynamically changing key operating parameters such as operating frequency, bandwidth, gain, beam direction, and signal polarization [9].

Antennas are typically made reconfigurable using variable reactive components such as varactors [41,42] and PIN diodes [43,44]. However, these semiconductor elements introduce parasitics and nonlinearities, which can limit their operational frequency range and reduce gain [43,44]. MEMS switches have been used effectively to reduce these parasitic effects [45], but this technology can require high actuation voltages.

Alternatively, this chapter demonstrates the use of Galinstan to reconfigure the lengths of a slot antenna's microstrip feed and radiating aperture. To use liquid metal as a conductive tuning element, enclosed fluidic channels are used to guide the metal and define its shape and range of motion. The liquid metal can be actuated by pressure either hydraulically or pneumatically within these channels [25,27,30,46–48], however, Galinstan and other gallium-based alloys develop an oxide film in the presence of oxygen in concentrations as low as 1 ppm [14]. This oxide film adheres to channel walls and impedes motion of the liquid metal. Therefore, reversible and repeatable reconfiguration must account for

the removal of this oxide, which in some cases has required evacuating the liquid metal and rinsing the channel with ethyl alcohol [46], or the immersion of the liquid metal in Teflon solutions [48].

Alternatively, the liquid metal can be immersed in a strong acid or base [49, 50], which chemically reduces the oxide layer and prevents it from reforming. The use of electrolytic carrier fluids also allows for surface-tension-based actuation techniques [2, 51, 52] that are both low voltage and low power. However, aqueous solutions have unacceptably high loss tangents at microwave frequencies [53], and while careful channel design can minimize its impact on device performance [54], some degradation in gain and efficiency is unavoidable.

In contrast to these techniques, this chapter presents liquid metal actuated by pressure-driven air bubbles. This process incurs fewer RF losses than CEW actuation while remaining reversible and repeatable. This technique is demonstrated to dynamically reconfigure the length of the radiating aperture and feed line of a slot antenna to enable reconfigurability.

4.2 Air-Bubble Actuation of Liquid Metal

The air-bubble actuation method is accomplished by surrounding the liquid metal with a thin layer of 1% NaOH solution in a hydrophobic channel that is otherwise filled with air. The NaOH solution enables movement of the liquid metal by reducing any oxidation as well as by acting as a slip layer [55] (Fig. 4.1.a) between the liquid metal and the channel walls. Because the channel walls are hydrophobic, the NaOH solution does not adhere to

the walls and instead wets to the liquid metal, following its motion.

Figure 4.1: (a) Liquid-metal slug coated in a thin layer of NaOH in a hydrophobic channel in a balanced air pressure environment. (b) Motion induced by a pressure differential $P_1 > P_2$.

To implement air-bubble actuation, the channel is first filled with the 1% NaOH solution. A finite volume of liquid metal is then injected into the channel to form a slug. The NaOH solution is then evacuated, leaving only a thin NaOH layer surrounding the liquid-metal slug. This minimizes the exposure of the aqueous solution to the RF. To induce motion of the liquid-metal slug, a pressure differential sufficient to overcome the channels hydraulic resistance is created between the two sides of the slug P_1 and P_2 . When the pressure differential is positive between P_1 and P_2 , the liquid-metal slug shifts from left to right (Fig. 4.1.b). Reversing the pressure differential reverses the motion. This pressure differential can be created a number of ways including pneumatically, hydraulically, or through the thermal expansion of air. For this device, manual control of a 1-mL syringe is

used to pneumatically pump the air.

4.3 Reconfigurable Slot Antenna Design

4.3.1 Liquid-Metal Reconfigurable Aperture and Feed

The slot antenna design consists of a rectangular slot in the ground plane of an open-circuited microstrip feed (Fig. 4.2). The slot presents an impedance to the microstrip line, which depends on the slot dimensions, feed point location, and stub length [56]. The resonant frequency of the slot is found when its length is approximately half of a guided wavelength.

Figure 4.2: Slot antenna layout.

The antenna is made frequency reconfigurable by incorporating liquid-metal slugs at each end of the slotline (Fig. 4.3.a) and at the end of the microstrip feed (Fig. 4.3.b).

The liquid-metal slugs positioned over the slotline create RF shorts that effectively shorten the length of the slot, thus increasing its resonant frequency. The liquid-metal slug on the microstrip feed varies the electrical length of the open-circuited tuning stub, and can be used to cancel out any parasitic reactance introduced by the slot tuning. Inlets and outlets at the end of the channel allow for pneumatic actuation of air to create the pressure differential for air-bubble actuation. Liquid-metal slugs may be pushed by injecting air to create a positive pressure differential, or pulled with the evacuation of air to create a negative differential. For the manual actuation of this prototype the inlets and outlets are temporarily sealed with a few drops of NaOH solution to maintain the pressure in the channel.

4.3.2 Fabrication

The slot antenna is implemented on Rogers Duroid 5880 substrate with a thickness of 0.79 mm and $\epsilon_r = 2.2$. The static copper slot dimensions are $W_s = 1.0$ mm and $L_s = 60$ mm as shown in Fig. 4.2. The copper 50- Ω microstrip feed has a width W_m of 2.4 mm and extends up to, but not beyond the center of the slot, thus L_m is 0 mm. Fluidic channels are fabricated over the slot as well as the microstrip feed. The channels consist of 0.6-mm-thick polyimide walls and a 1-mm-thick polystyrene ceiling all resting on top of a 0.1-mm-thick polyimide floor (Fig. 4.4). This polyimide floor prevents the liquid metal and copper from coming into direct contact as gallium readily reacts with copper [38]. The channels are coated with PTFE using an inexpensive solution of Duraglide, making them hydrophobic.

(a)

(b)

Figure 4.3: Fabricated liquid-metal slot antenna: (a) slot (b) microstrip feed.

Figure 4.4: Cross section of the slot antenna and micro-channels.

Repeatable control of the position of the liquid metal within the channels is of critical importance to the antennas performance. To this end, the channels are constructed as a series of interconnected circular chambers, which create discrete points of minimum surface energy for the liquid metal [2]. The strong surface tension of liquid metals ensures that the slugs will be drawn to these discrete positions, making the actuation consistent and reliable [2]. The channels at each end of the slot have chambers with a diameter of 3.7 mm, and a 3.0-mm center-to-center spacing (Fig. 4.3.a), while on the microstrip feed the chambers have a diameter of 2.4 mm with a 2.0-mm center-to-center spacing (Fig. 4.3.b).

4.4 Experimental Results

The fabricated slot antenna is shown in Fig. 4.3. At each end of the slot an 8-chamber-long (24.7 mm) liquid-metal slug is injected into the channel. The microstrip feed has a 16-chamber-long (32.4 mm) slug. These liquid-metal slugs initially rest completely above the copper and have little to no effect on the slot antenna.

Figure 4.5: Measured S_{11} of the fabricated slot antenna as the feed length beyond the slot and slot length are reconfigured.

The antenna has an initial resonant slot length of 60 mm and an open-circuited microstrip feed that extends to the center of the slot. The antenna is frequency reconfigured by pneumatically moving the liquid-metal slugs at each end of the slot in increments of 3 mm, to shorten the slot by a total of 6 mm. Because the slot line is shortened equally on each side, the feed point is preserved in the center of the slot. Thus the impedance of the slot does not change much from state to state and only requires fine tuning of the feed length at the edges of the tuning band. Eight states are measured until the slot has a length of 30 mm. The measured S_{11} of the eight discrete states (Fig. 4.5) span across a contiguous 26% tuning bandwidth (TBW) from 1.42 GHz to 1.84 GHz for which the S_{11} is less than -10 dB.

Table 4.1: Liquid-metal slot antenna state summary

State	L_s [mm]	L_m [mm]	f_c [GHz]	FBW [%]
1	60	8	1.42	4.36
2	60	6	1.49	5.40
3	54	6	1.53	5.66
4	48	6	1.62	5.35
5	36	6	1.68	5.52
6	30	6	1.74	5.33
7	36	4	1.79	4.49
8	30	4	1.84	4.04

The measured radiation patterns for State 1 and State 8 are shown in Fig. 4.6. The slot antenna has a peak gain of 4.8 dBi and 4.1 dBi respectively at each state. The measurements show that the antennas radiation pattern and gain are minimally changed between the lowest and highest frequency states. Table 4.1 summarizes the measurements at each antenna state with the lengths of the slot and feed. The eight reconfigurable states have FBW ranging from 4.04% to 5.66%.

Figure 4.6: Measured radiation patterns at State 1 (red O) and State 8 (blue Δ). (a) E-plane with $\theta = 0^\circ$ in the upper half and $\theta = 180^\circ$ in the lower half and (b) H-plane. The copolar measurements are shown in solid and crosspolar in dashed.

Table 4.2 compares the performance of this antenna to other frequency-reconfigurable slot antennas using liquid metal, PIN diodes, varactors, photodiodes, RF MEMS, and metasurfaces. The results from this antenna show that a comparable tunable frequency bandwidth is achieved, while maintaining a relatively high gain.

Table 4.2: Comparison of different frequency-reconfigurable slot antennas

Antenna & Year	Technology	Design	Frequency range [GHz]	Contiguous TBW [%]	Gain [dBi]
This work [40]	liquid metal	slot & feed	1.42 - 1.84	26	4.8 - 4.1
[54] 2014	liquid metal	slot	2.4 - 2.9	19	2 - 4
[2] 2014	liquid metal	feed	2.2 - 2.6	15.2	2
[46] 2013	liquid metal	slot	$\sim$ 4.4 - 5.6	$\sim$ 24	-
[43] 2005	PIN diode	slot	0.54 - 0.89	-	-1.1 - 0.7
[44] 2012	PIN diode	slot	2.2 - 4.75	-	1.9
[41] 2003	varactor	feed	4.69 - 4.87	4	-
[41] 2003	photodiode	feed	2.08 - 2.85	31	-
[45] 2012	RF MEMS	slot	1.56 - 3.3	-	0.6 - 5.2
[57] 2014	metasurface	metasurface	2.78 - 3.2	14	4.8

4.5 Summary

This chapter demonstrated the pressure actuation of air bubbles for a liquid-metal frequency-reconfigurable slot antenna. Unlike conventional pressure actuation, this technique uses a thin layer of a 1% NaOH solution to coat the liquid-metal slugs to make the motion reversible and repeatable. Eight frequency states are measured spanning a contiguous range from 1.42 GHz to 1.84 GHz for which the S_{11} is less than -10 dB, with FBW ranging from 4.04% to 5.66%. The antenna has a peak gain of 4.8 dBi and 4.1 dBi at its lowest and highest frequency states respectively. The TBW and gain are improved over similar liquid-metal slot antennas, which must use electrolyte filled channels for CEW ac-

tuation [54]. These results are also comparable to frequency-reconfigurable slot antennas implemented with varactors [41], PIN diodes [43,44], and MEMS switches [45]. A disadvantage of this antenna is the approximate one second switching speed achieved with manual pneumatic actuation via syringe. Future development would require the integration of an onboard pump, at which point the switching time can be reduced by reducing the volume of the liquid metal to be actuated (i.e. smaller channels) or by increasing the pressure differential. This combination of air bubbles and gallium-based slugs in a NaOH slip layer can potentially be used to develop other liquid-metal-based reconfigurable RF devices.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

Wireless communications has become a fundamental part of the developed world. The number of mobile-cellular subscriptions is expected to continue its explosive growth to over 9 billion by the year 2019 [1]. Over 6 billion of those subscriptions will include smart phones, tablets, mobile PCs, and mobile routers [1]. These trends are evidence of the ubiquity of wireless communications and that there is a great demand to improve these wireless networks with faster speeds, higher bandwidth, less latency, and greater coverage. These demands are alleviated in part by recent developments in integrated circuits and network standardized architectures such as LTE, however continued progress will require advances in the RF hardware of communication systems as well.

Mobile phones use different frequency bands for their various channels of communication from cellular to Wi-Fi, GPS, and BlueTooth to name a few. Cellular communications in particular, require the use of many multiple different frequency bands for backwards com-

patibility with 2G/3G cellular networks as well as for current 4G networks. The current architecture of RF front ends consists of redundant chains of components to process each frequency band of interest, however this redundancy can be reduced through the use of reconfigurable components. Furthermore, the potential savings of costs, complexity, and board space brought in by using reconfigurable components can be used to expand the capabilities of the device and work over a wider range of frequencies.

This thesis presented the development of nontoxic liquid metal as a dynamic element to create reconfigurable components for RF front ends. By taking advantage of the amorphous nature of fluids and applying them to the normally static metal features of conventional electronics, an entirely new class of reconfigurable electronics is enabled. A liquid-metal conductor avoids the nonlinearity of semiconductor components, and can be dynamically deformed and shifted to achieve different performance criteria. This research has the potential to impact the telecommunications and electronics industries, and can enable more effective and efficient use of the wireless frequency spectrum.

Three different types of devices were demonstrated: a frequency-tunable SIW cavity filter, an EBG phase shifter, and a frequency-reconfigurable slot antenna. The SIW cavity filter is made reconfigurable using liquid-metal perturbing posts. Hollow vias within the SIW cavity can be either filled with liquid metal or evacuated to tune the bandpass frequency of the filter. This approach is simpler and avoids the parasitics of alternative methods which require additional bias, control lines, and floating via posts.

The phase shifter is based upon EBG elements, which exist as voids within the ground plane of a microstrip line. The device consists three cascaded EBG lattices to enable

three different gradations in phase shift. Channels enclosed over these EBG elements allow liquid metal to turn on and off the elements to reconfigure the amount of phase shift. The total amount of phase shift of the device is limited by its simplistic EBG architecture, but could be improved by utilizing more sophisticated and compact designs.

Both the filter and phase shifter used conventional hydraulic pressure to pump their respective liquid metal elements to induce performance changes. These prototype devices, however, were not hermetically sealed and thus exposed the liquid metal to oxygen, which caused the liquid metal to oxidize and prevented reversing the actuation. Measurements between states of the device required rinsing the liquid metal with a 1% NaOH solution to remove the oxidation. In contrast to these conventional pressure actuated devices, an actuation method using pressure-driven air bubbles to move liquid metal was developed. This air-bubble actuation method is simple, inexpensive, reversible, repeatable, and does not incur significant RF loss. This technique is demonstrated to reconfigure the length of the radiating aperture and feed line of a slot antenna to enable frequency reconfigurability.

5.2 Future Work: Electrical Actuation of Liquid Metal

In this thesis, liquid metal has been shown to be an effective element to enable reconfigurable components for RF front ends. However, a caveat of these demonstrated prototypes is that pressure was applied manually to induce liquid-metal motion. Integration of these components into commercial devices would require an on-board pump, which can be bulky, costly, and power inefficient. Thus the development of a low-power, low-voltage, rapid liquid-metal actuation mechanism would greatly advance the field of reconfigurable

liquid-metal technology.

Currently the types of components which use electrically actuated liquid metal can be categorized into two broad divisions: the indirect actuation of liquid-metal wetted contacts and direct liquid-metal actuation. Liquid-metal wetted contacts have been used to create switches with less contact resistance and eliminate switch bouncing [58, 59]. Essentially the cantilever or beam-switching element is coated with liquid metal to replace the typical solid-solid contact with a liquid-solid contact. The switch is then actuated by deflecting the cantilever. This can be done through various forces such as electrostatic, magnetic, and thermal to name a few. In this sense, motion is induced indirectly to the liquid metal and therefore the range of motion is limited to the cantilever switching element.

On the other hand direct liquid-metal actuation is not anchored to the limits of another element and thus a much wider extent of physical reconfiguration is possible and should be the focus for future development. Direct electrical actuation of liquid metal is possible through the manipulation of the liquid metal's surface tension through a phenomenon known as electrocapillarity [60]. Various derivatives of electrocapillarity exist, such as electrowetting (EW) [61], electrowetting on dielectric (EWOD) [62], continuous electrowetting (CEW) [52], electrochemical oxide deposition [50], and electrocapillary actuation (ECA) [3]. Among these liquid-metal actuation techniques, only CEW and ECA fulfill the criteria of rapid liquid-metal deformation (~ 100 mm/s) with a low-voltage (less than 5V) and low-power electrical signal ($\mu\text{W} - \text{mW}$) [3, 52].

5.2.1 CEW and ECA operation¹

CEW and ECA electrically manipulate the surface tension of liquid metal immersed in an electrolytic solution to induce motion. An electrical charge builds up across the liquid-liquid interface of the two liquids, which is called an electrical double layer (EDL) [51]. The surface tension of the liquid metal is directly related to the potential across the EDL [51]. In CEW, an electrical bias is applied across the solution to create an asymmetry in the EDL potential, which in turn causes the surface tension to vary along the length of the liquid metal. This surface tension gradient causes the liquid metal to wet (i.e. flow) in a desired direction Fig. 5.1. A DC signal can be used to stretch the liquid metal (Fig. 5.1.a) or a square-wave signal can be used to reposition the liquid metal (Fig. 5.1.b).

Figure 5.1: CEW in a 2-mm-wide, 400- μ m-high rectangular channel with (a) 8 VDC used to stretch and (b) square-wave actuation used to reposition the liquid metal. Square-wave signal parameters are 8 Vpp, +3 VDC offset, 30 Hz, and 50% duty cycle [2].

To deform the liquid metal, ECA can be used by directly biasing the EDL with an external voltage [3]. These deformations can be held and reversed through electrochemical oxide deposition and recapillarity [63], respectively. The details of this process is detailed

¹The work presented in this chapter is based from [2, 3]

in [3] and is shown in Fig. 5.2.

Figure 5.2: ECA, electrochemical oxide deposition, and recapillarity used to manipulate, hold, and reverse the liquid-metal deformation [3]. (a) Liquid metal is held in a reservoir next to a channel, both of which are filled with a 1% NaOH solution. (b) The liquid metal is deformed with ECA by directly applying 4 VDC between the electrolyte at the end of the channel and the liquid metal held in the reservoir. (c) Electrochemical oxide deposition is used to hold the deformation by applying -10 VDC. The deformation retracts by approximately 4 mm (Δl) before the metal oxide growth is able to wet to the channel walls. (d) The liquid-metal deformation is held for approximately 12 seconds. (e) Recapillarity is induced by applying 4 VDC to reinitiate the liquid-metal deformation. (f) In the absence of all external electrical biases the NaOH solution eventually reduces the metal oxidation and allows the deformation to begin receding. (g) Eventually the liquid metal returns to the minimum surface energy point within the central reservoir

5.2.2 Future Work: Liquid-Metal Switch

The low-power, low-voltage, and rapid flow enabled by CEW combined with the low-loss characteristic of liquid metal has the potential to create an RF switch with advantages over current semiconductor and MEMS switches. An ideal switch would have low insertion loss, high isolation, high linearity, high power handling, and a fast switching speed, all while consuming no power and fitting within a small form factor [10]. Currently, no existing technology meets all of these criteria, but oftentimes the application allows for concessions to be made in some of these switch characteristics, while prioritizing others. This section presents preliminary results for the development of a liquid-metal switch with the goal of miniaturization in the future.

Figure 5.3: A 3.3-cm long $50\text{-}\Omega$ copper microstrip line (a) tapered down to a 1-mm wide 0.7-mm long section in the center to mimic a switch in the on state and (b) with the 0.7-mm long section removed to mimic a switch in the off state.

An initial scaled-up prototype switch fabricated out of copper tape is shown in Fig. 5.3. The circuit consists of two $50\text{-}\Omega$ microstrip lines tapered to a 1-mm-wide, 0.7-mm-long section in the center to mimic a switch in the on state (Fig. 5.3.a). The total length of the microstrip line is approximately 3.3 cm long. The 0.7-mm-long section in the center

of the microstrip line is then removed to mimic a switch in the off state (Fig. 5.3.b).

Figure 5.4: A 3.3-cm-long 50- Ω copper microstrip line (a) tapered down to a 1-mm-wide, 0.7-mm-long gap that is filled with a drop of liquid metal to mimic a switch in the on state and (b) with the gap filled with a 1% NaOH solution to mimic a switch in the off state.

A droplet of liquid metal is then placed to bridge the gap of the same microstrip line to mimic a liquid-metal switch in the on state (Fig. 5.4.a). The liquid metal is then replaced with a droplet of a 1% NaOH solution to mimic the liquid-metal switch in the off state as if the liquid-metal droplet was displaced by CEW actuation (Fig. 5.4.b).

Figure 5.5: Measured S_{21} of the switch (a) in the on state and (b) off state of the copper and liquid-metal prototypes.

The results of the two prototypes are compared in Fig. 5.5. The S_{21} in the on state is presented in terms of dB/cm (Fig. 5.5.a), which brings the insertion loss into context for

future miniaturization. The S_{21} in the off state is presented in Fig. 5.5.b and shows that the isolation is severely diminished when filling the 0.7-mm wide gap with a 1% NaOH solution. Thus any liquid-metal switch realized by CEW actuation would have to minimize the exposure of the RF signal to the electrolyte.

5.2.3 Air-Bubble Actuation via Liquid-Metal Slugs with CEW

This section presents the concept of pushing air bubbles with liquid metal driven by CEW to actuate an RF switch. In contrast to conventional CEW actuation, an air bubble is used to displace the aqueous electrolytic solution required for CEW actuation, and thus electrically isolate the ports of the switch to effectively turn the switch off. To turn the switch on, the isolating air bubble can be displaced by a liquid-metal slug to connect the two ports through CEW actuation. Similarly to reverse the actuation and turn the switch off, a liquid-metal slug on the opposite end of the air bubble can be used to push the air bubble back.

The driving of air bubbles via liquid-metal slugs with CEW is enabled by the channel design shown in Fig. 5.6. The top-down view of the channel is shown in Fig. 5.6.a. The channel consists of an electrolyte-filled central channel containing an air bubble with liquid-metal slugs on both ends of the air bubble (Fig. 5.6.a). Running parallel and connected to the central channel are capillary rails, which are also filled with electrolyte and are key to enabling CEW actuation [64]. Without the rails, the air bubble would electrically isolate the two ends of the channel and thus disable CEW actuation. In addition, the rails exist on a different vertical plane than the ports of the switch (Fig. 5.6.b). This is critical to allow the air bubble to electrically isolate the ports from the electrolyte.

Figure 5.6: Channel design required for air-bubble actuation via liquid-metal slugs driven by CEW (a) top-down view and (b) cross section.

Figure 5.7: An air bubble driven by a liquid-metal slug via CEW with a square-wave signal. Square-wave signal parameters are 8 Vpp, +3 VDC offset, 30 Hz, and 50% duty cycle.

Fig. 5.7 shows top-down microscope images of a liquid-metal slug pushing an air bubble in a 1-mm-wide, 300- μm -high rectangular central channel with 1-mm-wide, 100- μm -high capillary rails. A square-wave signal of 8 V_{pp}, +3 VDC offset, 30 Hz, and 50% duty cycle is used to the liquid-metal slug with CEW. An average speed of approximately 2 mm/s is achieved. This prototype channel successfully demonstrates the feasibility of the technique. To integrate this actuation technique for a switch, the channels must be miniaturized. Miniaturization is not only necessary for a desirable device package size, but will also allow the relative force of surface tension to become more prominent and thus increase the actuation speed of the liquid metal and air bubble. The effects of the electrolyte can also be further mitigated by reducing the relative size of the capillary rails. Further research and development is required to refine and optimize this technique for RF applications.

5.3 Commercialization Issues

Liquid-metal technology is still relatively new and is unproven in commercial devices. These recent developments in the actuation of liquid metal has brought the technology a step closer to commercialization. However, there are other aspects of liquid metal that require further research and development, such as material compatibility, packaging, and deposition.

To integrate liquid metals into commercial devices, the liquid metal must be compatible with the fabrication technology. However, gallium and gallium-based alloys are incompatible with many of the commonly used metals in MEMS fabrication [65]. Still there

are materials that are compatible with gallium such as titanium, tantalum, and tungsten, which do not react until temperatures greater than 400°C and higher are reached [38]. Furthermore, gallium is also compatible with graphite and organic materials, such as plastics and rubber [38].

In addition to material compatibility concerns, to take advantage of the liquid metal's fluidic properties, prevention of metal oxidation is critical. This can be accomplished by fabricating and hermetically sealing the component in an inert environment. In this regard, advancements for the packaging of MEMS components can potentially be leveraged [66, 67].

Lastly, the integration of liquid metal into commercial devices requires the accurate and precise deposition of the liquid metal. In the majority of components presented in research the liquid metal is deposited manually. An issue with depositing gallium is its high boiling points and low vapor pressure. Nonetheless, it is possible at temperatures greater than 750°C in a vacuum of at least 7.6×10^{-6} torr [68] and has been demonstrated for the fabrication of a liquid-metal microswitch [59]. Furthermore, deposition control of the size and density of gallium droplets has also been demonstrated [69].

Ultimately, further research and development is needed to refine and enable liquid-metal technology to fulfill the accuracy, longevity, and repeatability requirements for commercialization. These challenges can be justified as liquid metal is unique in its combination of conductive and fluidic properties. Liquid metal has enabled new capabilities in the field of microfluidics, MEMS, RF, and more. Optimization for specific applications have been necessary, but the advancements made in each field can be leveraged to further the gains

made in others. The limit of the potential utility of liquid metal has yet to be seen.

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