Tunable RF Devices Using Electrically Actuated Liquid Metal

Ryan C. Gough, *Student Member, IEEE*, and Wayne A. Shiroma, *Senior Member, IEEE*

***Abstract*—This paper discusses the development of low-voltage, low-power actuation techniques for the electrical control of liquid-metal RF tuning elements. These techniques allow non-toxic gallium alloys to be moved and shaped in a manner that is both more versatile and more energy efficient than using micro-pumps, the most common actuation technique found in the literature. In addition, it is also shown how gallium oxide can be used to 'self-actuate' the liquid metal, resulting in dramatic control without the need for an external power supply.**

***Index Terms*—Electrocapillarity, gallium alloy, liquid metal, reconfigurable architectures.**

I. Introduction

Liquid metals are an advantageous choice for creating tunable RF circuitry. Fluidic conductors are low loss and their response is entirely linear, giving them an advantage over more common variable-reactance semiconductor components. Over the past few years the effectiveness of liquid metal as a tuning element has been well demonstrated [1], and the recent emergence of non-toxic gallium alloys as an alternative to mercury [2] has only increased interest in this versatile material.

However, for most devices in the literature the actuation of the liquid metal is dependent upon externally applied pressure [3], [4]. While effective, this methodology requires the use of micro-pumps for automation, which are both bulky and inefficient.

This research demonstrates new electrical techniques for the rapid and repeatable actuation of gallium alloys. These techniques leverage the naturally high surface tension of the liquid metal, as well as the unique electrochemistry of gallium alloys, to exercise wide-ranging and high-fidelity control over the shape and position of a liquid-metal tuning element. By avoiding the use of micro-pumps, these techniques also achieve an order-of-magnitude reduction in the actuation voltage and required power consumption.

II. Research

Surface tension is a constrictive force experienced by all liquids, and is especially high in liquid metals (approximately 530 mN/m for Galinstan, a commercial gallium alloy [2], as opposed to approximately 72 mN/m for water at room temperature). Surface tension can also be affected by surface charge, as described by the Young-Lippmann equation:

$$\gamma = \gamma_o - \frac{1}{2}CV^2, \tag{1}$$

where γ is the surface tension, γ_o is the surface tension in the absence of surface charge, C is the per-unit capacitance across the interface between the liquid and its surrounding medium, and V is the voltage across the same interface [5]. Submerging liquid metal in an electrolyte results in the creation of surface charge, which affects the interfacial tension between the liquid metal and the electrolyte as described in (1).

Our research has demonstrated that by electrically manipulating the distribution of this surface charge, non-toxic liquid metal can be moved in predictable, repeatable ways for the purposes of RF tuning [6], [7]. In [6] it was shown how non-toxic gallium alloys can be positioned with sub-millimeter accuracy anywhere within a fluidic channel, and with actuating voltages and power consumption requirements that are an order of magnitude below those of conventional micro-pumps.

More recently, we have shown that by compressing a finite volume of liquid-metal between two plates, mechanical boundary conditions are imposed which greatly heighten the sensitivity of the liquid metal to electrical manipulation [8]. This, in turn, can be used to rapidly actuate the liquid metal (linear speeds over 120 mm/s [8], see Fig. 1) and to form it into electrically useful shapes. In [9], a two-stage bandpass filter was introduced that used a central liquid-metal resonant element to determine the filter's passband. By stretching this element electrically, the passband can be lowered in an analog fashion across a 10% tunable bandwidth [9].

This research has also investigated the unique electrochemical properties of gallium alloys. By applying an oxidative potential between a reservoir of Galinstan and a surrounding alkaline electrolyte, gallium oxide can be grown on the surface of the liquid metal [10]. This oxide acts as a surfactant, significantly lowering the interfacial tension between the liquid metal and the electrolyte [10].

By taking advantage of the significant mechanical properties of this oxide layer, this research has demonstrated that it can be used to 'freeze' the liquid metal into non-minimum energy states [8]. This allows the liquid metal to maintain induced deformations that it would otherwise be unable to sustain.

This work was supported in part by the IEEE MTT-S Graduate Student Fellowship.

R. C. Gough and W. A. Shiroma are both with the Electrical Engineering Department, University of Hawai'i at Mānoa, Honolulu, HI 96822 USA (e-mail: rgough@hawaii.edu).

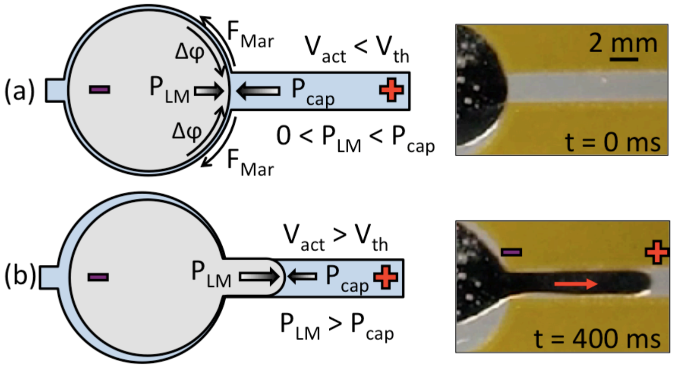

Fig. 1. (a) A positive bias relative to the liquid metal results in a surface tension gradient; the liquid metal begins exerting pressure on the channel entrance. (b) When this pressure exceeds the capillary pressure of the channel, flow is induced (4 VDC in the image on the right-hand side). Figures adapted from [8].

Furthermore, this mechanical stability can be turned on and off like a switch through the use of low-voltage electrical signals [8]. It is envisioned that this technique can be used to form the liquid metal into electrically useful shapes, at which point it can be held in these positions indefinitely.

Finally, we have also demonstrated that this same oxide growth can be initiated via redox reaction by using the liquid metal as an anode within a larger galvanic cell [11]. This allows the liquid metal to 'self-actuate', so that large-scale motion can be accomplished without the need for an external power supply – all of the kinetic energy comes from the stored electrochemical energy within the liquid metal itself [11]. This has significant implications for future work in ultra-low-power sensing and autonomous robotics, among other fields.

III. Future Plans

It has been a tremendous blessing to have received a Graduate Fellowship from the IEEE MTT-S. This scholarship has had an enormous impact on my work, and has directly contributed to multiple publications ([7], [8], [11]) as well as others that are still in the editing process. In addition, attending the International Microwave Symposium (IMS) in 2013–2015 was an invaluable experience – the conference simultaneously broadened my outlook and sharpened my research. The experience has also inspired me to become more involved in the MTT-S. I am now serving as Student Paper Competition Chair on the IMS2017 Steering Committee, Vice Chair of the University of Hawai'i MTT-S Student Branch Chapter, and Secretary of the MTT-S Hawai'i Chapter.

In May of 2016 I will graduate with a PhD in Electrical Engineering from the University of Hawai'i at Mānoa. I am very grateful for the time I have spent at this wonderful university, and am especially grateful for the mentorship of my advisors, Dr. Wayne Shiroma and Dr. Aaron Ohta. In June of 2016 I will begin work as an RF engineer for a Hawai'i-based company that designs and develops radar and communications

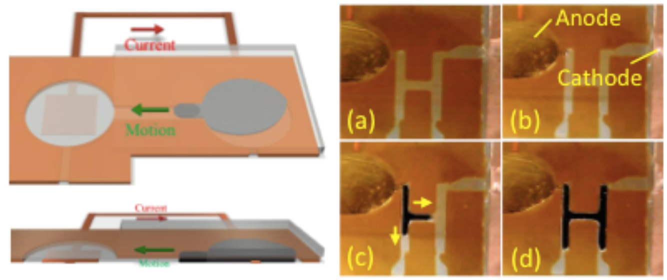

Fig. 2. Gallium alloys submerged in an alkaline electrolyte can serve as an anode, driving an oxygen reduction reaction at a copper cathode. The oxide growth resulting from this reaction causes liquid metal flow, which can be harnessed to form arbitrary shapes. This actuation does not require an external power supply. Figure adapted from [11].

systems. I am very excited to begin this next chapter of my career, and look forward to being an advocate for both the IEEE and the MTT-S in these beautiful islands for years to come.

References

[1] J. H. Dang, R. C. Gough, A. M. Morishita, A. T. Ohta, and W. A. Shiroma, "Liquid-metal-based reconfigurable components for RF front ends," *IEEE Potentials*, vol. 34, no. 4, pp. 24–30, Jul. 2015.

[2] T. Liu, P. Sen, and C.-J. Kim, "Characterization of nontoxic liquid-metal alloy Galinstan for applications in microdevices," *J. Microelectromechanical Syst.*, vol. 21, no. 2, pp. 443–450, Apr. 2012.

[3] A. P. Saghati, J. S. Batra, J. Kameoka, and K. Entesari, "A microfluidically reconfigurable dual-band slot antenna with a frequency coverage ratio of 3:1," *IEEE Antennas Wirel. Propag. Lett.*, vol. 15, no. 99, pp. 122–125, 2016.

[4] D. Rodrigo, L. Jofre, and B. A. Cetiner, "Circular beam-steering reconfigurable antenna with liquid metal parasitics," *IEEE Trans. Antennas Propag.*, vol. 60, no. 4, pp. 1796–1802, Apr. 2012.

[5] J. Lee and C.-J. Kim, "Surface-tension-driven microactuation based on continuous electrowetting," *J. Microelectromechanical Syst.*, vol. 9, no. 2, pp. 171–180, Jun. 2000.

[6] R. Gough, A. Morishita, J. Dang, W. Hu, W. Shiroma, and A. Ohta, "Continuous electrowetting of non-toxic liquid metal for RF applications," *IEEE Access*, vol. 2, pp. 874–882, 2014.

[7] R. C. Gough, R. C. Ordonez, M. R. Moorefield, W. A. Shiroma, and A. T. Ohta, "Reconfigurable liquid-metal antenna with integrated surface-tension actuation," accepted for presentation at the *11th Annual IEEE International Conference on Nano/Micro Engineered and Molecular Systems (IEEE-NEMS)*, Matsushima, Japan, 2016.

[8] R. C. Gough, A. M. Morishita, J. H. Dang, M. R. Moorefield, W. A. Shiroma, and A. T. Ohta, "Rapid electrocapillary deformation of liquid metal with reversible shape retention," *Micro Nano Syst. Lett.*, vol. 3, no. 1, 2015.

[9] R. C. Gough, J. H. Dang, A. M. Morishita, A. T. Ohta, and W. A. Shiroma, "Reconfigurable coupled-line bandpass filter with electrically actuated liquid-metal tuning," in *2014 Asia-Pacific Microwave Conference Proceedings (APMC)*, 2014, pp. 932–934.

[10] M. R. Khan, C. B. Eaker, E. F. Bowden, and M. D. Dickey, "Giant and switchable surface activity of liquid metal via surface oxidation," *Proc. Natl. Acad. Sci.*, vol. 111, no. 39, pp. 14047–14051, Sep. 2014.

[11] R. C. Gough, J. H. Dang, M. R. Moorefield, G. B. Zhang, L. H. Hihara, W. A. Shiroma, and A. T. Ohta, "Self-actuation of liquid metal via redox reaction," *ACS Appl. Mater. Interfaces*, vol. 8, no. 1, pp. 6–10, Jan. 2016.