Enabling Reconfigurable All-Liquid Microcircuits via Laplace Barriers to Control Liquid Metal

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***Abstract*— Liquid metals such as gallium alloys have a unique potential to enable fully reconfigurable RF electronics. One of the major concerns for liquid-metal electronics is their interaction with solid-metal contacts, which results in unwanted changes to electrical performance and delamination of solid-metal contacts due to atomic diffusion of gallium at the liquid/solid interface. In this paper, we present a solution to this problem through way of liquid-metal/liquid-metal RF connections by implementing Laplace barriers, which control fluid flow and position via pressure-sensitive thresholds to facilitate physical movement of the fluids within the channels. We demonstrate RF switching within the channel systems by fabricating, testing, and modeling a reconfigurable RF microstrip transmission line with integrated Laplace barriers which operates between 0.5–5 GHz. This approach opens the potential for future all-liquid reconfigurable RF electronic circuits where physical connections between solid and liquid metals are minimized or possibly eliminated altogether.**

***Keywords*—reconfigurable electronics, liquid metal, gallium alloy, EGaIn, microfluidic electronics**

I. Introduction

Physically reconfigurable electronics using liquid-metal conductors has been gaining traction due to the promise of highly tunable and adaptable performance not capable in MEMS or electrically tunable approaches [1], [2]. The capability of microfluidics for precision control of fluids on a chip offers a favorable platform for integration with microwave circuits, where the precise geometry of conductors and dielectrics define their performance in the RF. Recently, eutectic gallium-indium (EGaIn) alloys have been used with success as deformable and reconfigurable conductors [1]–[4] as they remain liquid at room temperature, have a high conductivity (3.40×10^6 S/m), and are non-toxic, unlike mercury. Furthermore, with judicious selection of various co-fluids and microfluidic designs, these liquid metals can be actuated by either pneumatic or electrostatic methods [5]–[7], and chemical approaches are being developed to eliminate the adhesion of the surface-to-channel walls [8]–[10].

One of the primary challenges to implementing physically reconfigurable liquid metals as RF components involves the interactions between the mobile liquid material (typically a gallium alloy such as EGaIn) and traditional microcircuit metals such as gold, silver, and copper. These materials readily alloy, resulting in pinning of the metal that impedes the release of the liquid from the solid-metal contacts, rendering reconfigurability difficult. It has also been shown numerous times that the alloying between gallium-based fluids and solid metals can lead to damage of the traditional circuit [11]. One solution to this problem is to eliminate liquid/solid contacts and utilize entirely liquid/liquid interfaces to reconfigure the RF circuit. However, the high surface tension of liquid metals render them particularly tricky to confine and retain in their designated locations. These concerns are overcome here by utilizing a microfluidics mechanism in which control over the liquid-liquid interface is enabled through Laplace barriers [12]. Laplace barriers have been used with success as pressure thresholds for liquid metal microcircuits [13], [14], yet a full characterization of their effect on creating liquid/liquid connections within microcircuits has not been studied.

In this paper, a straightforward switchable microstrip transmission line is chosen to demonstrate the utility of Laplace barriers in controlling liquid metal within microchannel circuits. The transmission line is designed, modeled, fabricated, and tested with Laplace barriers separating a liquid/liquid electrical connection to employ an RF switch in an integrated RF board. It is demonstrated here that Laplace barriers can be implemented to minimize and potentially eliminate solid/liquid metal interfaces in the future within RF liquid-metal tunable components.

II. Device Design

An RF microstrip transmission line is designed and fabricated that includes an integrated microfluidic channel which is used to house liquid metal EGaIn. The EGaIn can be switched pneumatically between a closed and an open state to connect or disconnect the transmission line, respectively. Vertical Laplace barriers are fabricated at the interface between two actuating EGaIn lines in the middle of the channel orthogonal to the channel direction. These Laplace barriers abruptly restrict the width of the channel throughputs and sharply increase the required back pressure needed to push the fluid through. A co-fluid of aqueous NaOH (<1M) is used to strip away the oxide coating that forms naturally on the surface to better demonstrate the proof-of-principal operation of the Laplace barrier to control liquid metal; however, the concept is not limited to the use of this co-fluid, and could be employed with any number of mobilizing techniques found in the literature [5]–[10]. Fig.

1 shows the overall design schematic and structure of the Laplace barriers at the location of the liquid-metal connection.

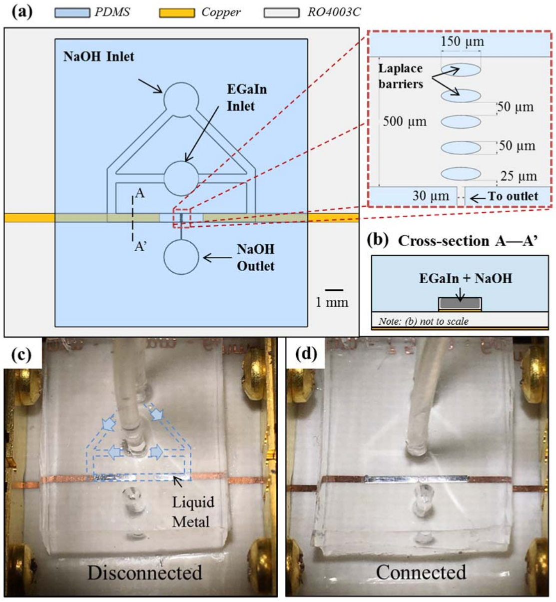

Fig. 1. (a) Schematic of integrated microfluidic microstrip device with inset depicting Laplace barrier dimensions. (b) Cross-section view of device layers. (c) Image of disconnected device prior to pressure loading. Channels and fluid flow are highlighted (d) Image of a connected device with liquid metal merging at the Laplace barrier.

A. Microfluidics and Laplace Barrier Designs

A microfluidic channel containing an array of pillars aligned perpendicular to the direction of fluid flow is used to confine the liquid metal into separated transmission-line elements. Pillar arrays provide the necessary threshold between disconnected and connected states. To fill a cross-sectional area of the microchannel with liquid metal, the applied pressure must exceed the pressure drop ΔP across the interface between the liquid metal and the surrounding fluid. This pressure is defined by the Young-Laplace equation:

$$\Delta P \equiv P_{inside} - P_{outside} = 2\gamma\left(\frac{1}{H}+\frac{1}{W}\right) \qquad (1)$$

Here P_{inside} is the pressure within the liquid metal and $P_{outside}$ is the pressure in the surrounding fluid; γ is the interfacial tension between liquid metal and the surrounding fluid; H and W are the microchannel height and width, respectively.

In a monolithic microfluidic device, the channel height H is uniform. However, the alignment of Laplace barriers across the channel as shown in Fig. 1(a) decreases the channel width W through which the liquid metal interface must flow, thereby increasing the pressure required according to (1). This pressure threshold scales with the interfacial tension of the fluid interface, which is advantageous for EGaIn due to its high reported interfacial tension values [3], [15]. This property makes the Laplace barrier a particularly effective method for confining liquid-metal microfluidics.

The pressure threshold set by the Laplace barriers is constant and predictable, allowing for controlled breaching of the barrier by the liquid metal. Thus, two separated liquid-metal segments in contact with either side of the barrier will remain physically isolated until an applied pressure above the threshold from either side causes them to close the separation distance between them, and eventually merge.

Pillars of 50-µm width at 100-µm pitch are chosen to accommodate the desired pressures and facilitate fabrication. A length of 150 µm is selected for the pillars, forming ellipsoidal cylinders in order to ensure the liquid metal has sufficient spacing to achieve good isolation in the off state. A height of 80 µm is used for the microfluidic channel.

B. Integrating Microfluidics and Microwave Circuits

Due to the quasi-TEM nature of microstrip transmission lines, care must be taken when introducing new materials onto a standard RF board to ensure a good match between the device under test (DUT) and the surrounding network. Fringing fields above the signal trace will see the top material, so when integrating the PDMS microfluidics, the dielectric properties of the PDMS used must be considered in the design.

1) PDMS Integration and Microstrip Design

Dielectric properties of PDMS are determined from *S*-parameter measurements performed in an X-band waveguide cavity. The VNA is calibrated via a Thru-Reflect-Line (TRL) method. An additional quarter-wavelength line waveguide section is used as the sample holder, with the PDMS cast and cured directly into the waveguide section, preventing air gaps. *S*-parameter measurements are sent to Keysight Materials Measurement software, and the NIST iterative measurement model is selected for dielectric property extraction. Measured ε' of the sample has low dispersion, ranging from about 2.80 down to 2.77 from 8.2 to 12.4 GHz, respectively. Measured loss tangent ranges from 0.019 to 0.025 over the same range, respectively. While we later report device operation in frequencies from 0.5–5 GHz, due to the low dispersion of the measured PDMS in the X-band, we use the upper bound of 2.80 to estimate the relative permittivity in our band of interest.

With the microfluidic material characterized, the design of a matched transmission line can be achieved. The challenge is finding a suitable RF board that provides a sufficient thickness to yield a matched transmission line for the embedded microstrip, given the fixed geometry of the channel that defines the liquid-metal trace. The effective permittivity of the RF board with the PDMS microfluidics is determined using a numerical method employing the technique of Green's function to solve electric potential in an embedded microstrip with boundary conditions prescribed by the materials, following the methods from [16]. From this method, an effective permittivity of the embedded structure can be extracted.

A selection of RF board is made that yields a proper effective relative permittivity for an available board thickness to achieve as close to a 50-Ω transmission line as possible. A 305-µm (12 mil) thick RO4003C board with dielectric constant 3.38 provides an effective permittivity of 3.320. For a board height of 305 µm, trace width of 500 µm and trace thickness of 80 µm, an impedance of 51.7 Ω is determined.

2) Fabrication

The microstrip board is fabricated with a roll-to-roll etch process (C.I.F). The boards are brushed and laminated with a dry film resist before being patterned by UV exposure. After development and etching, the resist is removed, completing the copper microstrip structures.

The microfluidic channels containing Laplace barriers were fabricated from PDMS using standard soft lithography methods. A negative mold of the microchannel design was photopatterned in a layer of SU-8 2025 (Microchem) epoxy photoresist on silicon wafers using a transparency mask and MA6 mask aligner (Karl Suss). PDMS (Sylgard 184) was prepared by mixing the base and curing agent in the standard 10:1 ratio by weight using a planetary mixer (Thinky). The mixture was poured over the SU-8 mold, degassed for 5 minutes and cured at 65 °C for 2 hours. The cured PDMS was cut from the mold and access ports were cored through the PDMS using a 1.5-mm biopsy punch.

A thin film of PDMS is needed to provide a suitable bonding surface of the microchannels to the substrate. First, the edges of the board with the copper transmission lines are masked with Kapton tape, to a distance of 3 mm from the edge of the board. This length selected is important in the section below covering de-embedding. Next, PDMS is spin-coated directly onto the RO4003C board at 4000 rpm and cured, achieving a thickness of 20 µm. The Kapton is then removed, leaving 3 mm lengths of copper bare for electrical connection to the RF test fixture. The microfluidic devices are cut to span the entire length of the transmission-line device, except for the 3-mm lengths of bare copper at either edge. The PDMS surfaces are then plasma treated (Harrick) for 30 seconds to generate hydroxyl groups on the surface containing the channels. The microchannel is then aligned with the copper microstrip structure and pressed together to form the bond.

III. Device Operation and Performance

The device performance is measured with a microstrip test fixture (Anritsu Universal Test Fixture) that acts as an adapter for the 3.5-mm coaxial cables from the VNA to the microstrip board. The test fixture is calibrated with a microstrip calibration kit (Anritsu 36804-10M) using TRL standards. A Beatty standard is used to verify the integrity of the calibration. It is important to note that this calibration does not account for reflections at the interface of the bare RO4003C board and the PDMS covered board.

Prior to the introduction of EGaIn, the microfluidic channels are filled with a solution of NaOH in deionized water. This co-fluid is necessary to prevent the oxide that forms at the EGaIn surface, enabling the EGaIn to flow through the microchannel without adhering to the PDMS surface. The main downside is that water is very lossy in the microwave spectrum and could have a large impact in device performance, depending on the device configuration. Since most of the energy in a microstrip is stored within the board dielectric below the trace, this configuration provides minimal negative effect of the lossy co-fluid.

The device is dosed with liquid metal using a pressure displacement system (Nordson Ultimus IV) until the liquid metal fills only the channel segment aligned above the copper microstrips from opposing sides of the Laplace barriers. One of the inlets is then blocked, and the system is then pressurized from the other inlet port to merge the liquid metal between the Laplace barriers, forming a single transmission line, acting like an RF switch from port 1 to port 2. Fig. 2 depicts images of the microfluidic system at the Laplace barriers as well as *S*-parameter measurements of the device from 0.5–5 GHz.

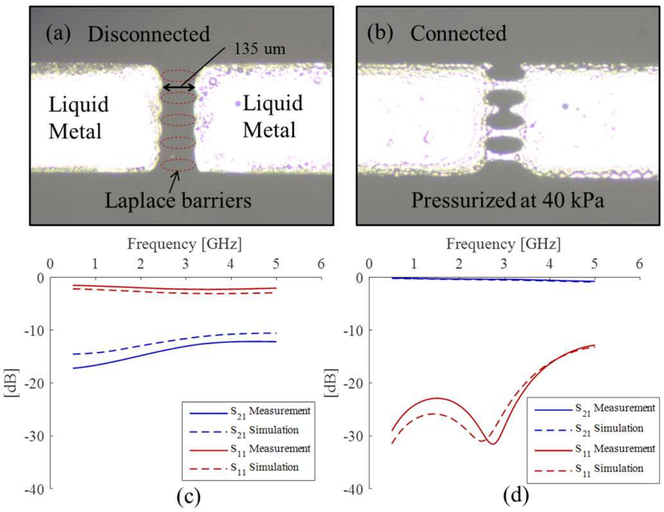

Fig. 2. (a) Image of the unconnected microstrip before threshold pressure is applied. (b) Applying 40 kPa of pressure to the channel causes the EGaIn to bridge the gaps between Laplace barriers, connecting the device. (c) *S*-parameter data of the disconnected and (d) connected devices.

When unconnected at the Laplace barrier, the 135-µm gap provides 15 dB of isolation between microstrip lines. Once pressurized, the EGaIn displaces the NaOH solution within the gaps, forcing the co-fluid to flow into the exit channel at the bottom sidewall adjacent to the barriers. Upon connection, the transmission line insertion loss becomes -0.104 dB at 0.5 GHz, and increasing to -0.758 dB at 5 GHz.

The precise effect of the merging that occurs between the barriers is shown in Fig. 3, where two different merging cases are compared to the simulated fully connected case. As more points of connection between barriers arise, the insertion loss seen in the microstrip device drops.

IV. De-embedding the DUT

To get a better understanding of the effects the Laplace barrier connection alone has on device performance, a de-embedding procedure that isolates the device under test (DUT) must be used. A custom TRL calibration kit is developed and implemented within the VNA's measurement. The standards for the integrated RF board are fabricated in parallel with the devices. Results of measurement following this de-embedding procedure can be seen in Fig. 4.

The line calibration piece is measured as a copper reference to determine the loss we see with the integrated RO4003C and PDMS board for 8.5 mm transmission line. The EGaIn device is then measured in the case of 3 merged connections, similar to as depicted in Fig. 2(b). By storing the S_{21} copper reference data to memory and measuring the EGaIn device, the VNA math function Data/Memory is used to subtract the loss from the copper line from the EGaIn line, to view how using the Laplace barriers with EGaIn and NaOH together impacts the overall insertion loss. At 2 GHz, the effect of using EGaIn to bridge the Laplace barriers incurs an added loss of only 0.2 dB.

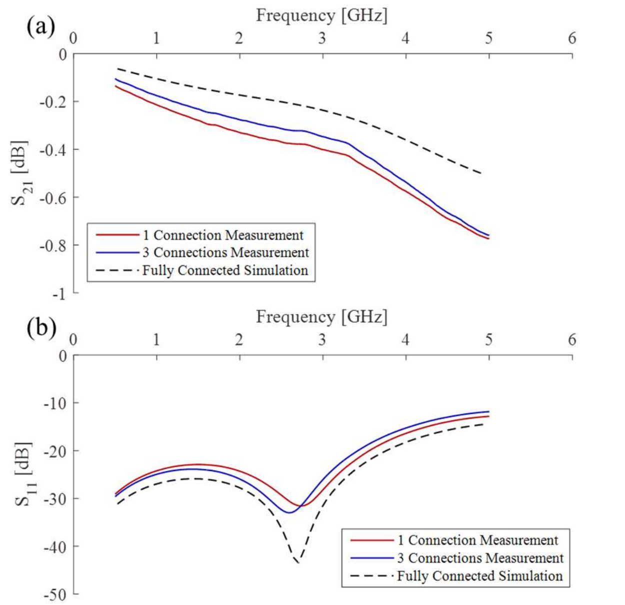

Fig 3. Measurements and simulation of (a) S_{21} and (b) S_{11} for various cases of liquid-metal connection in the gaps between the Laplace barriers.

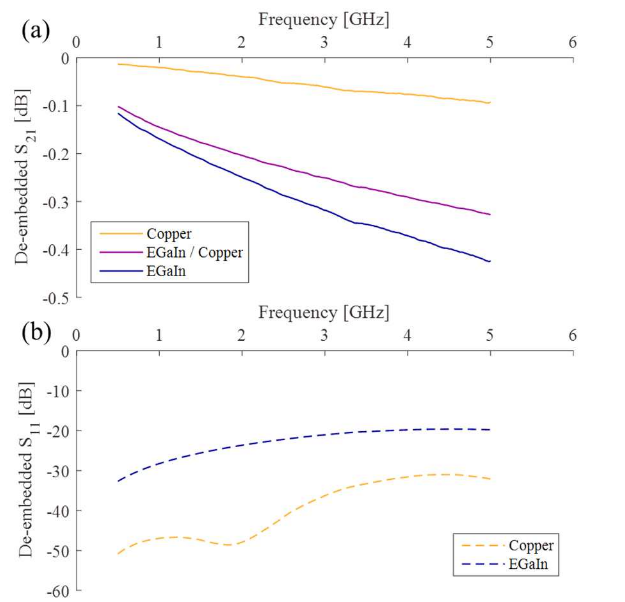

Fig. 4. (a) Measured S_{21} for the copper Line standard and EGaIn device with 3 connections across the barrier. EGaIn/Copper depicts the loss associated by replacing the copper Line with the EGaIn line (b) Measured S_{11} values for the copper and EGaIn microstrip lines.

V. Conclusion

The integration of a microfluidic channel containing Laplace barriers into a microstrip transmission line on an RF board was presented that enables a controllable method of connecting or isolating liquid-metal microstrip structures. The demonstration of a controlled liquid/liquid connection for microfluidic RF devices allows controllable reconfigurability without undesired liquid/solid metal interactions. The Laplace barriers serve as a restraining force to confine the liquid-metal microstrip elements as a function of pressure, allowing designers and engineers to select when and how to reconfigure the microstrip circuit without unwanted fluid transfer. This microfluidic approach can further be optimized by varying the effective barrier threshold, allowing for pneumatic or electrostatic actuation and is easily scalable for multiple connections within a more complex circuit. The barriers allow for designable isolation between microstrip elements, and their threshold can be graduated, allowing for multiple actuation states within a single device. The inclusion of these barriers shows a minimal increase to insertion loss in the transmission line when characterized with a de-embedding procedure, thus enabling a controllable reconfigurable microwave circuit design that is composed of liquid/liquid interfaces.

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