Liquid-Metal Balun and Amplifier for Reconfigurable RF Front Ends

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***Abstract*—This paper discusses two liquid-metal-based devices designed for use in reconfigurable radio frequency (RF) front ends. A tunable log-periodic balun with retractable liquid-metal legs operates across three continuous bands from 1.89 to 8.45 GHz. The two output ports have a magnitude balance within 1 dB and a phase difference within 10° of 180°. A tunable amplifier with reconfigurable liquid-metal matching networks can be configured to multiple frequency states from 3.37 to 6.02 GHz. This actuation is achieved via the direct application of low-power, low-voltage signals, allowing for simplified integration with existing RF architectures.**

***Index Terms*—Reconfigurable architectures, liquid metal, continuous electrowetting.**

I. Introduction

RECONFIGURABLE circuits are a popular topic for wireless RF applications, promising more capable multi-band communication systems. Conventional designs use varactors, PIN diodes, and MEMS to alter a system's frequency response. Liquid metal has also proven to be effective for reconfigurability, and has been used to create RF switches, antennas, and filters. This paper demonstrates the use of liquid metal to tune the frequency response of two devices, a three-state log-periodic balun [1] and double-stub input and output matching networks of an amplifier. We believe these to be the first instances of liquid metal being used to create a tunable balun and amplifier.

The liquid metal used in these devices is Galinstan, a non-toxic gallium-based alloy [2]. Galinstan remains a liquid from -19˚C to 1300˚C, making it practical to use across a wide range of environments. The Galinstan used here is kept immersed in a 1% NaOH solution in order to prevent the formation of a highly wetting oxide layer.

II. Liquid Metal Log-Periodic Balun

Baluns are essential in providing an interface between unbalanced and balanced feeds in many wireless systems involving antennas, mixers, and balanced amplifiers. Balanced output ports have equal magnitude and opposing phase. The microstrip log-periodic balun is based on the N-section half-wave balun and log-periodic antenna [3].

The proposed layout in Fig. 1 consists of nine liquid-metal channels that are used to control the frequency band of operation. Three channels are used per state: the lengths l_1 to l_3 are used for State 1 (low-frequency state), l_4 to l_6 for State 2 (mid-frequency state), and l_7 to l_9 for State 3 (high-frequency state). Using the equations from [3], an approximation for the lengths required for each of the three states was made. Using Keysight's Advanced Design System (ADS) and Momentum, the design was then optimized for the appropriate frequency band of interest and a final layout was simulated.

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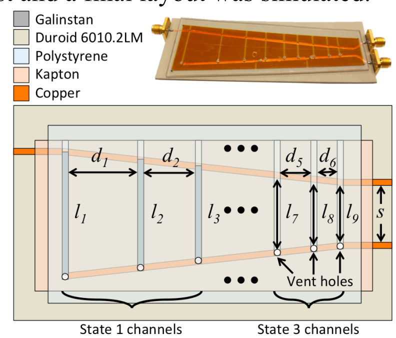

Fig. 1. Layout and design of the three-state log-periodic balun. Inset depicts fabricated device.

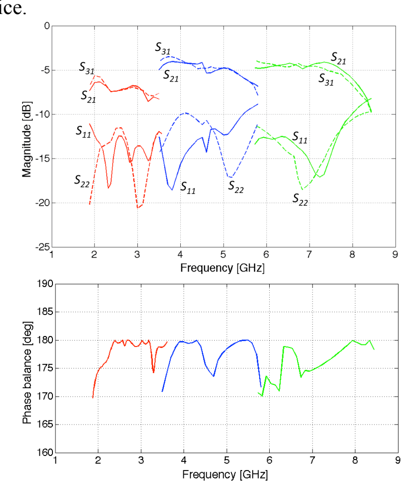

Fig. 2. Top figure: insertion (S_{21} and S_{31}) and return loss (S_{11} and S_{22}) measurements of the fabricated balun for State 1 (red), State 2 (blue), and State 3 (green). Bottom figure: phase difference.

Figure 2 demonstrates continuous coverage across all three states. State 1 spans 1.89 to 3.61 GHz, State 2 spans 3.37 to 5.80 GHz, and State 3 spans 5.46 to 8.45 GHz. Over these bands, the three states have balanced outputs within 1 dB and phase balances within 10° of 180°. The return loss for all three states is typically better than 10 dB (for clarity, S_{33} is not depicted but is very similar to S_{22}). The insertion loss ranges from 1 dB to 7 dB. State 1 has about 2 dB more loss than the other states, which we attribute to the solution used to clean the channels from State 2 and 3.

III. Liquid-Metal Amplifier

A double-stub impedance tuner consists of two shunt open- or short-circuited transmission-line stubs spaced λ/8 apart, whose lengths are continuously variable from 0 to λ/2 to maximize impedance coverage [4]. Reconfigurable amplifiers use impedance tuners to optimize characteristics such as gain, frequency, noise, and efficiency.

Figure 3 illustrates the amplifier layout consisting of the transistor, stabilizing network, and tuners. The transistor is an Avago ATF-35143 and designed to be unconditionally stable for frequencies above 3 GHz, using a gate-to-source 442-Ω resistor and a 100-pF series capacitor acting as a DC choke. The transistor was biased at V_{GS} = -0.37 V, V_{DS} = 3.0 V, and I_{DS} = 30 mA through the network analyzer ports.

Liquid-metal double-stub tuners with lengths l_1 to l_4 form the input and output matching networks. The fabricated device is shown in Fig. 3. The design uses RT/Duroid 5880 substrate with a thickness of 0.79 mm, ε_r=2.2. The separation distance d_1 between adjacent stubs is 3.81 mm, which is not the conventional λ/8 spacing, but was found through ADS optimization in order to maximize the tunable bandwidth. The distances d_2 to d_4 were similarly optimized: d_2 is 22.86 mm, d_3 is 5.21 mm, and d_4 is 25.40 mm.

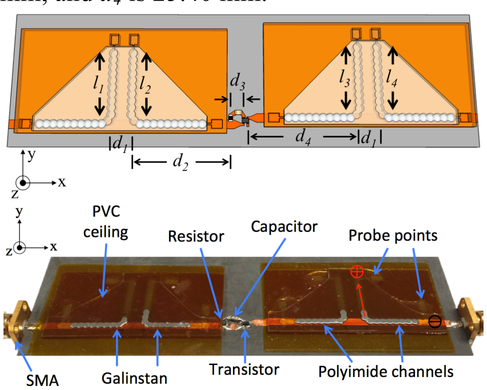

Fig. 3. Reconfigurable liquid-metal tunable amplifier, showing: (top) layout of double-stub tuners whose lengths l_1 to l_4 can be physically altered to vary the frequency response of the amplifier, and (bottom) photo of the fabricated device.

The liquid metal is contained in L-shaped channels that sit above the 50-Ω microstrip lines as shown in Fig. 3. When actuated, the liquid metal extends out perpendicular to the microstrip lines, creating tuning stubs of variable length. The interlocking circular chambers that comprise the channel act as minimum surface energy points, and allow the position of the liquid metal to be controlled incrementally. In this way the stub length can be varied from 0 to 19.1 mm, or ten 1.91 mm spaced chambers. To actuate the liquid metal, a 20-Hz, 10-Vpp square-wave signal with +4V DC offset and 50% duty cycle is used. The actuation method is known as continuous electrowetting (CEW) and is detailed in [6] and [7]. Less than 10 mW is required for actuation – a desirable feature for low-power devices.

The ten demonstrated actuation states shown in Fig. 4 typically improve the baseline state by 2 dB in the 3.37 to 5.5 GHz range with at least 10 dB input and output return loss. For comparison, a conventional non-liquid-metal amplifier simulated in ADS with the same stabilization network resulted in a maximum available gain (MAG) of 2 to 3 dB higher than its unmatched state. Therefore, the gain improvement due to impedance matching is comparable to that of a static copper amplifier design, but with the added benefit of frequency tunability. The amplifier can be tuned from 3.37 to 6.02 GHz, beyond which the loss due to the electrolyte overwhelms the gain that can be achieved by impedance matching.

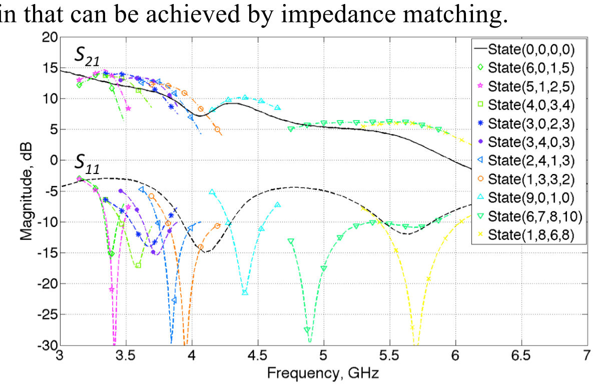

Fig. 4. Measurement of several states of the tunable amplifier. The frequency can be tuned to multiple states just under an octave. The S_{21} (top half) and S_{11} (bottom half) are depicted. The S_{22} is not shown but is similar to the S_{11}.

IV. Conclusion

A multi-state tunable balun and amplifier were demonstrated using liquid metal. This is the first demonstrated use of liquid metal to create a frequency-tunable amplifier and balun.

V. Acknowledgements & Future Plans

I would like to thank MTT-S for this scholarship and Dr. Wayne Shiroma for advising me throughout this project. The MTT-S Scholarship program not only gives young engineers like myself an opportunity to develop professionally, but also supplies vital funding for relevant and interesting projects. This project was made possible by MTT-S Scholarship funding and resulted in a first-author conference publication in IMS 2014 [1]. In addition, it provided financial assistance that helped me attend the 2014 European Microwave Conference, an important and horizon-expanding networking opportunity that would otherwise have been completely out of my reach.

I graduated with my M.S. degree in Electrical Engineering in the Fall of 2014 from the University of Hawaiʻi at Mānoa. I have recently accepted a position at Northrop Grumman as a RF microwave design engineer.

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