Predictive Design of a Liquid-Metal Switch Actuated by Continuous Electrowetting

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***Abstract*—A liquid-metal switch actuated by continuous electrowetting is designed and simulated using varied concentrations of sodium hydroxide electrolyte as the immersive media. The observed strong agreement between simulated and measured switch characteristics suggests that the behavior of similar liquid-metal-based systems may be predicted through simulation, eliminating the need for inefficient trial-and-error physical prototyping.**

***Index Terms*— Circuit simulation, liquid metal, microwave devices, permittivity, sodium hydroxide (NaOH).**

I. Introduction

Continuous electrowetting (CEW) of liquid metal (LM) has been demonstrated to enable reconfigurability in a variety of electronic components including terahertz waveguides [1], antennas [2], and switches [3]. CEW operates via the application of an electric potential across a LM slug immersed in electrolyte solution, most commonly aqueous sodium hydroxide (NaOH) [4]. Another method of electronic actuation in LM systems, electrocapillarity, also uses NaOH solutions as an immersive media [5]. While these techniques enable compatibility with integrated-circuit technology, the effects of NaOH solutions in these devices have remained difficult to predict a priori. Instead a lengthy trial-and-error development process has been used, increasing the cost and time of development.

Recent work [6] has demonstrated the ability to use measured complex permittivity spectra of NaOH solutions at microwave frequencies to simulate designs of NaOH-containing LM devices. Going forward, such simulations may be integrated into the design process, enabling improved device functionalities and development rates.

This paper demonstrates the ability to simulate, and thereby predict, the operational characteristics of an LM device containing an NaOH solution. Using a CEW-based single-pole single-throw LM switch as the proof-of-concept device, we isolate the effect of the NaOH solution, thereby verifying the ability to predict NaOH-related effects and providing insight into its function in similar architectures. This demonstrates that further iterations of the design process could be done to optimize the device performance, without the need for physical prototyping. Together with the determination of CEW actuation speeds, this enables similar devices to be predictively engineered.

II. Design and Methods

Fig. 1 is a schematic of the switch design. The channel structure consists of seven circular chambers (diameter = 2.35 mm, center-to-center spacing = 1.9 mm), a geometry first described in [4]. The channel is first filled with NaOH solution and then three chambers are filled with Galinstan, a gallium-based room-temperature liquid metal [7]. The channel structure rests on a 50-Ω microstrip line with a 2-mm gap in the center. In the ON state, the LM slug is positioned directly over the gap enabling a capacitive connection between the microstrip on either end of the gap. In the OFF state, the LM slug is actuated towards port 1 (Fig. 1) and resides over the microstrip. Actuation by CEW is achieved using a 30-Hz, 6-VPP square wave with 2-Vdc offset (50% duty cycle).

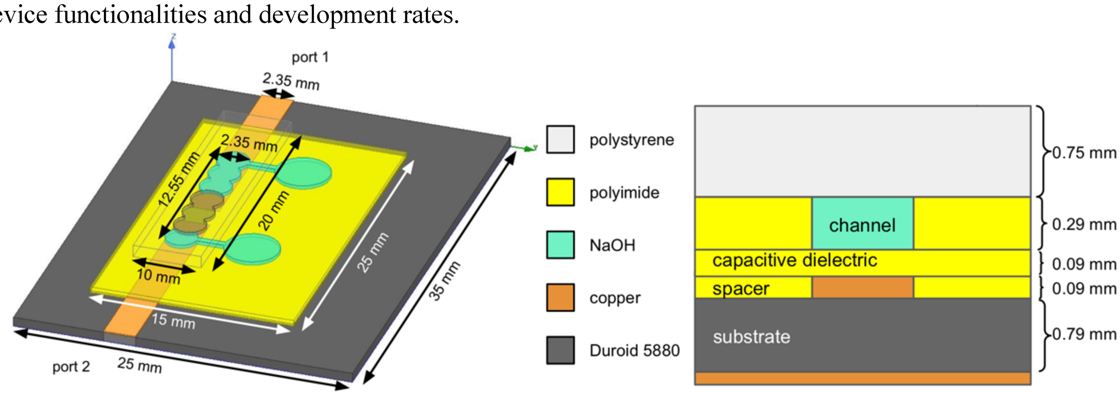


Fig. 1. ANSYS HFSS model of switch in the ON state with dimensions (left) and schematic of cross section (right, not to scale).

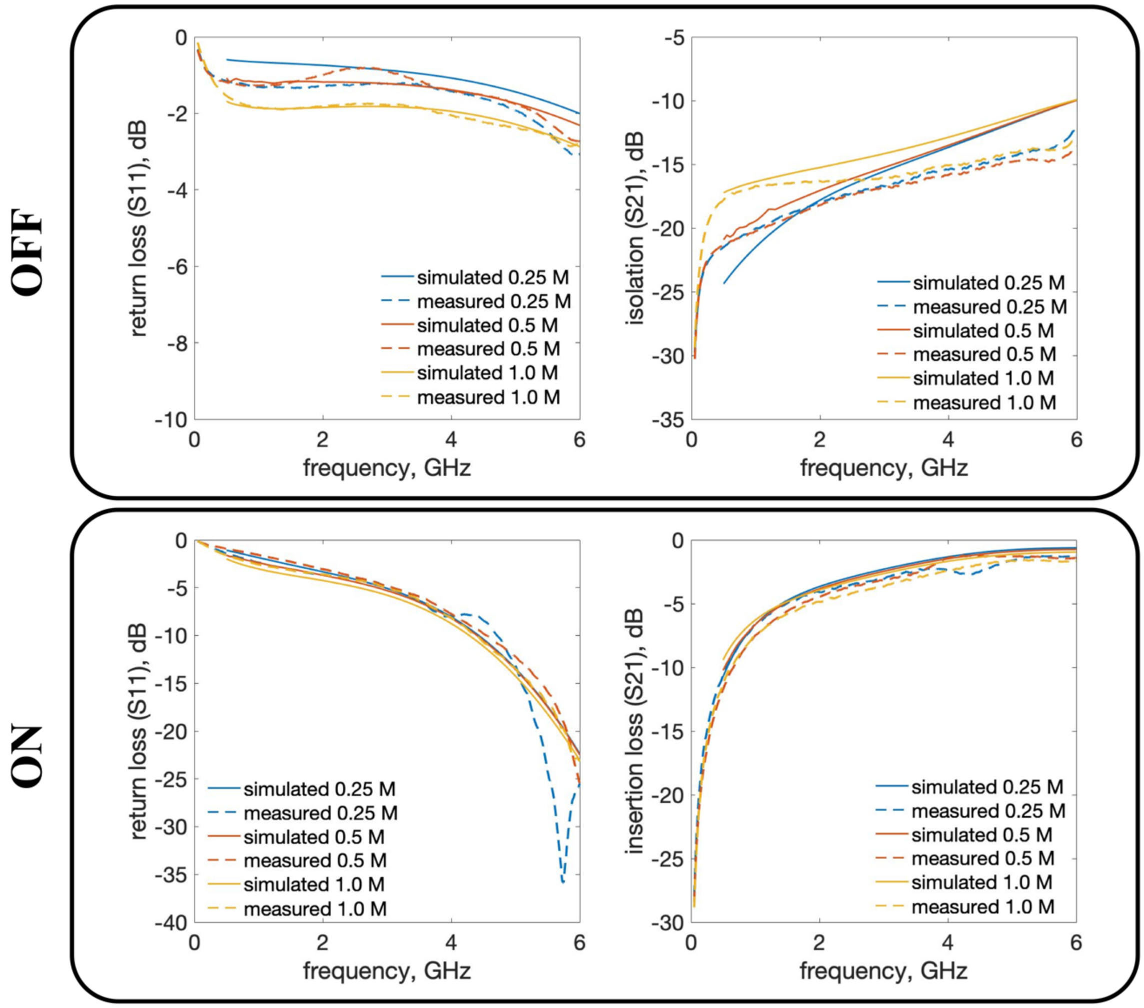


Fig. 2. Plots of the return loss (S_{11}) and isolation/insertion loss (S_{21}) parameters of the device in both the OFF and ON states. Near total reflections at near-dc frequencies in the ON state is a result of the capacitive connection established in the ON state.

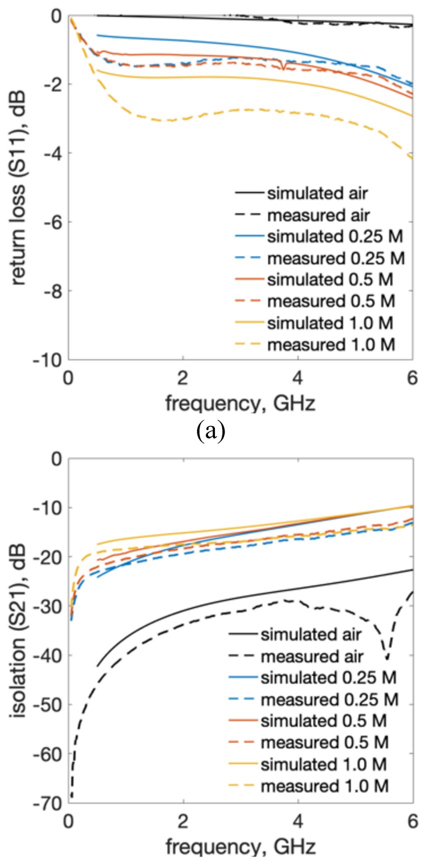
An identical signal is used to actuate LM to measure actuation speeds. A longer scalloped channel (31 circular chambers) of identical diameter and spacing to the switch was set on a polystyrene substrate. Using a high-speed camera (240 fps), the velocities of a LM slug (also three chambers in length) were determined with different molarities of NaOH. The slug was actuated 10 times with the average velocity of each end-to-end trip being measured via frame counting.

The switch was modeled in ANSYS HFSS electromagnetic simulation software. The NaOH was made from a custom material model using measured complex permittivity spectra.

III. Results and Discussion

Fig. 2 shows the measured and simulated return loss, isolation, and insertion loss of the switch in the ON and OFF states. Overall there is good agreement between the dispersion of simulated and measured *S*-parameters. A relatively uniform difference between the measured and simulated values occurring across all measurements is indicative of overall losses/leakage due to imperfect fabrication and modelling. Differences in simulated relative values (between varied concentrations) are typically on the order of 1 dB or less where noise from fabrication and measurement nonuniformities is significant.

The overall small differences in switch performance at varied NaOH concentrations demonstrates that the switch geometry is not sensitive to the small changes in conductivity and permittivity associated with different molarities of NaOH. Although the concentration does not strongly affect the device performance, the presence of NaOH has a significant effect. Fig. 3 shows the *S*-parameters of the switch geometry when the channel is filled with only NaOH at varied concentrations or air. The data in this figure is measured without inclusion of LM, isolating the effect of NaOH itself.



(b)

Fig. 3. The (a) return loss (S_{11}) and (b) isolation (S_{21}) of the device without LM in the channel.

The more pronounced disagreement of the simulated values relative to all measured curves at lower frequencies in Fig. 3(a) suggests that this difference originates from the model itself and is not related to NaOH losses. Likewise, the missing dip at approximately 5.5 GHz in the simulated curve for the air-filled channel in Fig. 3(b) occurs where the measured and simulated curves for NaOH-filled channels is maximal, also indicating that the base model is the origin of such discrepancies.

Together, these results suggest that for LM devices where the amount of NaOH relative to the overall size is similar or smaller, the exact molarity will not strongly affect device performance in the 3–6 GHz range. This removes the design constraint of a particular molarity when considering performance in similar cases.

With this degree of freedom other concentration-dependent design parameters may be optimized. For CEW-based devices, the LM actuation speed – and hence the reconfiguration rate – fundamentally depends on the concentration of the immersing NaOH solution. Table I shows the concentration dependence of CEW actuation speeds as an average over 10 trials. The exact values are largely dependent on channel and fabrication parameters which must be determined on a case-by-case basis.

TABLE I
ACTUATION SPEEDS AT VARIED CONCENTRATIONS

Concentration (mols/L)	Average Speed (mm/s)	Standard Deviation (mm/s)
0.25	18.4	0.774
0.5	20.8	0.478
0.75	18.4	0.463
1.0	18.8	0.496
1.5	15.5	0.781

Beyond 0.5 M the observed speed begins to decrease, resulting in a significant drop beyond 1 M. This is surprising as increased NaOH concentration is expected to increase the capacitance of the LM-NaOH interface providing a larger surface-tension variation with applied voltage according to the Young-Lippmann equation

$$\gamma = \gamma_0 - \frac{C}{2}(V - V_0)^2 \quad , \qquad (1)$$

where γ is the surface tension of the LM, γ_0 is the intrinsic surface tension, C is the capacitance per unit area across the LM-NaOH interface, V is the applied voltage across the interface, and V_0 is the intrinsic voltage across the interface [8]. However, the electrodynamics of CEW at the LM-NaOH interface requires further study to verify if this intuition is valid.

The authors posit that one of the mechanisms for decreased speeds at higher concentrations may be due to the formation of oxygen within the channel as a result of alkaline water electrolysis. At higher concentrations this effect would become more prevalent due to increased dissolved hydroxide groups. Moreover, the formation of small air bubbles along the walls of the channel have been observed after only a few seconds of applied signal. Significantly, electrolysis would only be possible if a LM slug is present to provide a potential difference within the channel, functioning as the electrodes. Again, further study of the electrodynamics at the LM-NaOH interface is necessary to verify if this is indeed the origin of the observed trend.

IV. CONCLUSION

This paper demonstrated the ability to predict the operational characteristics of a LM switch through simulation, suggesting that a wider class of LM devices may also be prototyped through simulation. Furthermore, the effect of NaOH within the switch was isolated and relative actuation speeds have been quantified enabling increased optimization of LM devices without inefficient trial and error.

Acknowledgment

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