Liquid-Metal Intelligent Reflecting Surfaces for Power-Efficient Wireless Communications

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***Abstract*— Liquid metal is demonstrated as an effective material for intelligent reflecting surfaces (IRS) unit cells operating at 28 GHz. This paper presents simulation results for two 1-bit liquid-metal IRS unit-cell designs: an electrically actuated design based on continuous electrowetting (CEW-1) and a mechanically actuated delay-line design (M-1). Both designs achieve approximately 180° of reflection phase shift between two operating states while maintaining high reflection magnitude. Array simulations of 8 × 8 IRS configurations verify anomalous reflection angles between 34° and 39° for quasi-periodic phase gradients. The mechanical design was fabricated and experimentally characterized, showing anomalous reflection within 3° of simulated predictions for normal plane-wave excitation.**

***Index Terms*—Liquid metal, intelligent reflecting surface (IRS), continuous electrowetting, anomalous reflection.**

I. Introduction

The deployment of 5G wireless networks enables high data rates and low latency, but performance remains strongly dependent on operating frequency. While millimeter-wave frequencies offer high throughput, they suffer from increased path loss and blockage, motivating techniques that actively shape the propagation environment [1]. Phased arrays and highly directional antennas can help, but their cost, power demands, and hardware complexity make them difficult to scale in dense scenarios [2]. Reflectarray-based intelligent reflecting surfaces (IRSs) offer a low-power alternative for extending coverage and mitigating line-of-sight (LoS) blockages without active RF chains [2]. A reflectarray imposes spatially varying phase shifts on incident waves to enable anomalous reflection and virtual line-of-sight links. Traditional reconfigurable reflectarrays rely on components like PIN diodes [3], varactors, MEMS switches, or tunable materials for phase control, but each has its own trade-offs related to power consumption, fabrication complexity, and scalability. To potentially address these limitations, this work explores liquid-metal-based intelligent reflecting surfaces, where physical reconfiguration of conductive elements enables stable phase tuning without the need for sustained biasing. This work investigates liquid-metal delay-line reconfiguration for 1-bit IRS unit cells operating at 28 GHz, a key band for 5G systems. Two representative designs are presented: a mechanically actuated unit cell (M-1) and an electrically actuated continuous-electrowetting unit cell (CEW-1). Their phase performance is evaluated through full-wave simulation, with experimental validation for the mechanical design.

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II. Design

A. Delay-Line Phase Tuning

Anomalous reflection from a quasi-periodic IRS can be predicted using the generalized Snell's law. For a phase gradient $\Delta\phi$ applied across adjacent unit cells with spacing Δx, the reflected angle θ_r is given by:

$$\theta_r = \sin^{-1}\left(\sin\theta_i - \frac{\lambda}{2\pi}\cdot\frac{\Delta\phi}{\Delta x}\right) \qquad (1)$$

where θ_i is the incident angle and λ is the free-space wavelength. This relationship is used to predict the steering angle of the simulated IRS arrays.

To realize the required phase gradient, both designs employ a reconfigurable delay-line element that overlaps the main radiating element. Two distinct physical delay-line lengths correspond to approximately 0° and 180° reflection phase states, denoted State 0 and State 1. Because the delay line overlaps the radiating element, the unit-cell resonance remains largely unchanged, while the added electrical length induces the desired phase transition. The actuation mechanism differs between designs. In Design M-1, the delay-line length is changed mechanically, with liquid metal maintaining electrical contact during motion. In Design CEW-1, liquid metal is displaced within a microfluidic channel using continuous electrowetting [4], altering the effective delay-line length electrically. Both liquid-metal IRS designs were developed using full-wave electromagnetic simulations in Ansys HFSS.

B. Electrical Design (CEW-1)

The unit-cell geometry is shown in Fig. 1. A microstrip patch resonator was selected for its simplicity and high reflectivity, while phase tuning was enabled by a movable Galinstan liquid-metal stub suspended above the resonator within a microfluidic channel composed of interconnected cylindrical reservoirs. Due to the small vertical separation between the stub and resonator layers (≈20 µm), capacitive coupling is preserved after actuation, modifying the effective electrical length of the combined structure. The complex reflection coefficient (S_{11}) was extracted for each liquid-metal position, and the corresponding reflection phase was used to define the available phase states for array synthesis.

The CEW-1 unit cell uses a 4 mm × 5 mm periodicity with a microfluidic delay-line stub positioned approximately 20 µm above the radiating element to enable capacitive coupling. For actuation, the base configuration (State 0) uses a fixed volume of Galinstan overlapping the radiating element. When a low-power square-wave signal is applied, CEW displaces the

Galinstan along the channel until it reaches a stable extended position (State 1) increasing the effective electrical length of the element and producing an around 180° of reflection phase shift.

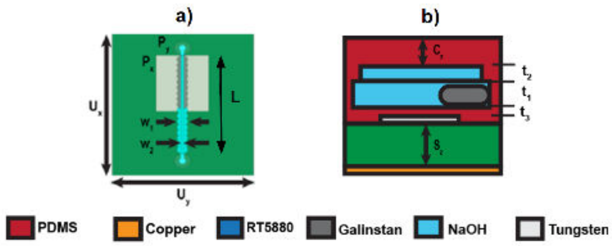

Fig. 1. CEW-1 unit-cell model: a) top-view and b) side-view

C. Mechanical Design (M-1)

Design M-1 serves as a proof-of-concept to the more complicated Design CEW-1 and is shown in Fig. 2. The electrical delay-line movement is replaced with a mechanical actuation. The unit cell consists of a copper radiating element patterned on a Rogers RT/duroid 5880 substrate with a copper ground plane, and a copper delay-line element patterned on a Borofloat 33 glass superstrate. A 100-µm air gap between the radiating element and delay line is filled with a Galinstan droplet, which readily wets to copper and maintains electrical continuity during motion. Mechanical linear motion extends the delay line to form State 1 while the Galinstan droplet preserves electrical continuity.

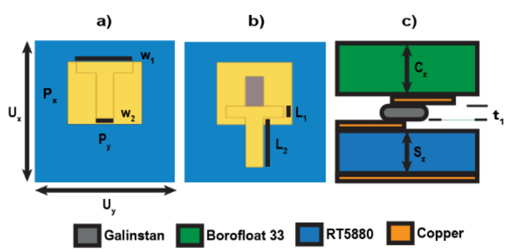

Fig. 2. M-1 unit-cell model: a) top-view and b) side-view

III. Results and Discussion

Array-level simulations were performed for both Designs CEW-1 and M-1 using finite 8 × 8 IRS configurations. The simulated bistatic radar cross section for each design is shown in Fig. 3, where the response for a uniform State 00-00-00-00 configuration is compared against a quasi-periodic 00-11-00-11 phase pattern. For both designs, the uniform configuration produces primarily specular reflection, while the quasi-periodic phase gradient results in anomalous reflection at angles consistent with predictions from (1).

To experimentally validate the simulation framework, a prototype IRS based on Design M-1 was fabricated and measured in an antenna range. Fig. 4 compares the measured and simulated bistatic radar cross section for the fabricated M-1 array under normal plane-wave excitation. The measured anomalous reflection angle agrees with simulation within approximately 3°, confirming the validity of the liquid-metal delay-line concept. Minor discrepancies are attributed to alignment tolerances and unintentional air gaps between the substrate and superstrate layers.

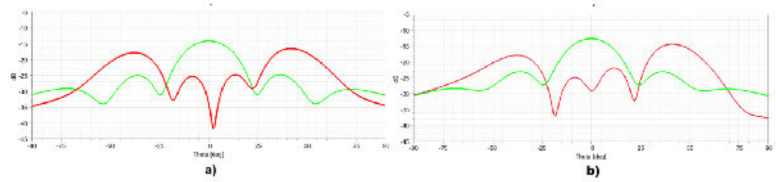

Fig. 3. Simulated bistatic RCS of 8x8 finite arrays of a) CEW-1 and b) M-1.

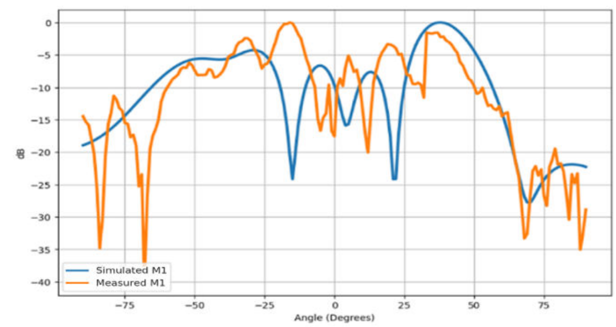

Fig. 4. Measured vs simulated bistatic RCS of a fabricated M-1 prototype.

IV. Conclusion

This paper presents electrically and mechanically reconfigurable 1-bit IRS unit cells based on liquid-metal delay-line tuning at 28 GHz. Design CEW-1 establishes the feasibility of electrically actuated liquid-metal phase control through simulation, demonstrating discrete phase switching without moving solid components. Design M-1 provides experimental validation of the liquid-metal delay-line concept, achieving near-180° reflection phase shift and anomalous reflection consistent with simulations. Together, these results highlight liquid metal as a low-power, low-complexity alternative for phase control in millimeter-wave IRS architectures.

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References

[1] W. Tang, X. Chen, M. Z. Chen, J. Y. Dai, Y. Han, M. D. Renzo, S. Jin, Q. Cheng and T. J. Cui, "Path loss modeling and measurements for reconfigurable intelligent surfaces in the millimeter-wave frequency band," *IEEE Trans. Commun*, vol. 70, no. 9, p. 6259–6276, Sept. 2022.

[2] M. Matthaiou, O. Yurduseven, H. Q. Ngo, D. Morales-Jimenez, S. L. Cotton and V. F. Fusco, "The road to 6G: ten physical layer challenges for communications engineers," *IEEE Commun. Mag.*, vol. 59, no. 1, pp. 64-69, Jan. 2021.

[3] T. J. Cui, M. Q. Qi, X. Wan, J. Zhao and Q. Cheng, "Coding metamaterials, digital metamaterials and programmable metamaterials," *Light: Sci. & Appl.*, vol. 3, no. 10, Oct. 2014.

[4] 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.

[5] M. Kouchi, G. A. Manio, S. Dacuycuy, K. Maki, R. Ordonez, C. Aguilar, C. Hayashi, W. Shiroma, and A. Ohta, "Reconfigurable intelligent surface unit-cell designs utilizing liquid metal for phase tuning," *2025 IEEE Int. Symp. Ant. & Propag.* Ottawa, Canada, Jul. 2025.