Continuous Electrowetting Surface-Wave Fluid Antenna for Mobile Communications

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Abstract — **In this paper, a reconfigurable fluid antenna that utilizes continuous electrowetting (CEW) techniques for achieving agile radiation pattern was presented. The proposed CEW method can electronically shift the position of the liquid metal on the surface-wave antenna. The travelling speed of the liquid metal when immersed in sodium hydroxide electrolyte of different concentrations, and biased under different control signal voltages and waveforms have been experimentally evaluated, the results show that the maximum travelling speed of the liquid metal is about 10 mm.s^{-1}. The antenna operates in a wide frequency range from 23.5 to 38 GHz, which covers the Very High 5G Frequency band in the different countries. The simulation results show that the addition of CEW geometry will not significantly affect the overall performance of the antenna.**

Keywords—reconfigurable antenna, fluid antenna, liquid metal, Galinstan, MIMO, surface wave, beam-steering, continuous electrowetting

I. Introduction

MIMO, one of the most famous wireless communication technologies in the past three decades, is being continuously promoted and applied as well as updated and iterated. This is mainly due to its high spectrum utilization efficiency, which makes full use of existing spectrum resources to gain both reliability and effectiveness by utilizing space resources[1]-[8]. However, this technique is difficult to implement in portable devices due to the limited internal space of the devices [9]. Thus, it is challenging to design a handheld antenna system that not only has the advantages comparable to those multiple-antenna MIMO systems, but also works with the current MIMO base stations. Therefore, the concept of fluid antenna was born as a result.

Fluid antennas are a type of reconfigurable antenna. One of its most appealing features is that it can be reconfigured to suit different communication environments and need. Spatial diversity is a good embodiment of this characteristics, and it can be achieved by shifting the position of fluid radiator [10]. Moreover, it has been theoretically demonstrated that a compact single-element fluid antenna system (FAS) could deliver a lower outage probability when compared with the conventional L-antenna maximum ratio combining (MRC) system [11]. Thus, to realize the proposed FAS platform, a method to shift the fluid radiator in the channel quickly and precisely is needed. Meanwhile, the ease of integration and the impact of the drive method on the overall system performance also need to be considered.

Therefore, the continuous electrowetting (CEW) is proposed as the drive method in FAS. The movement of the liquid metal is controlled by applying a voltage to the two electrodes in the electrolyte, thereby changing the surface tension of the liquid metal [12]. Furthermore, subsequent experiments have also demonstrated that this driving method basically has negligible impact on the overall performance of the antenna, while providing fast moving speed. It is easy to integrate the technique in the surface-wave fluid antenna structure [13].

II. Antenna Geometry

The 3D view of the geometry of the proposed continuous electrowetting single-fluid-channel surface-wave antenna is shown in Fig. 1. The electromagnetic simulation model includes a piece of PCB with a surface wave launcher, a fluid container, a liquid metal radiator , a K-connector, two biasing pads and electrolyte.

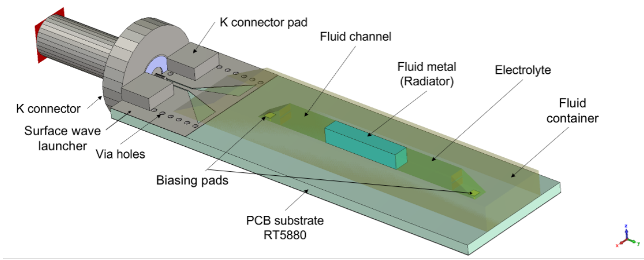
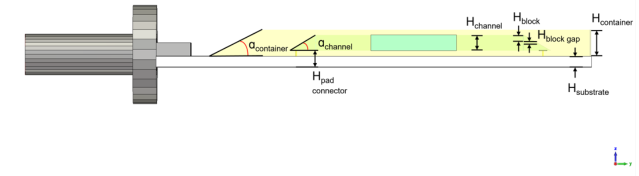


Fig. 1. The 3D view of the proposed antenna design

The surface wave platform of the antenna is built on a piece of Rogers RT5880 microwave dielectric substrate (ε_r = 2.2, thickness = 0.8 mm and tan δ = 0.0009 at 10 GHz), it has a ground plane on the bottom side and the surface wave launcher etched on the top side. The fluid container sitting on the top of the PCB is made of epoxy resin (ε_r = 4.0) which is 3D printed. This container includes a fluid channel as well. Inside the fluid channel, there is the liquid metal radiator (Galinstan: electric conductivity = 3.46×10^6 S/m, thermal conductivity = 16.5 W/K/m, material density = 6440 kg/m^3, thermal diffusivity = 8.65578×10^{-6} m^2/s)[13] and electrolyte (0.5% NaOH: ε_r = 79, electric conductivity = 5.491 S/m; 1% NaOH: ε_r = 74.5, electric conductivity = 10.143 S/m; 1.5% NaOH: ε_r = 72, electric conductivity = 14.796 S/m; 2% NaOH: ε_r = 68, electric conductivity = 19.449 S/m) [14]. The K-connector part, biasing pads and electrolyte are included in the model for studying the potential impact of them on the antenna performance, particularly, the radiation patterns.

The detail of the antenna structure is illustrated in Fig. 2. The pads are used as electrodes to supply the voltage which actuate the fluid radiator. The overall dimension of the antenna structure without the K-connector is ($L_{substrate}$ × $W_{substrate}$ × ($H_{container}$ + $H_{subsrate}$)), 33 × 10 × 2.8 mm^3. The detailed dimensions have been given under the caption of **Error! Reference source not found.**. CST 2021 was used in all the electromagnetic simulations.



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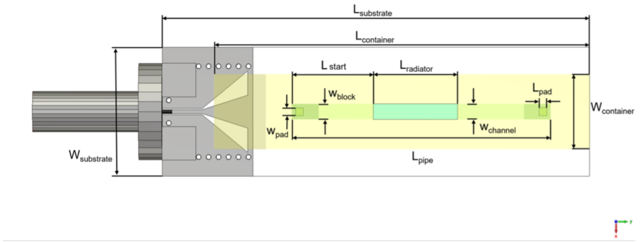

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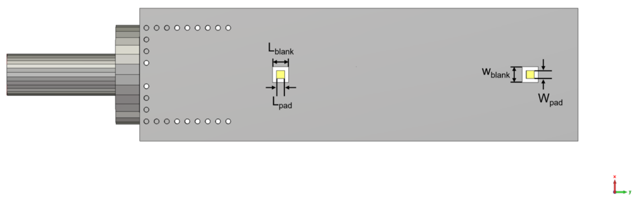

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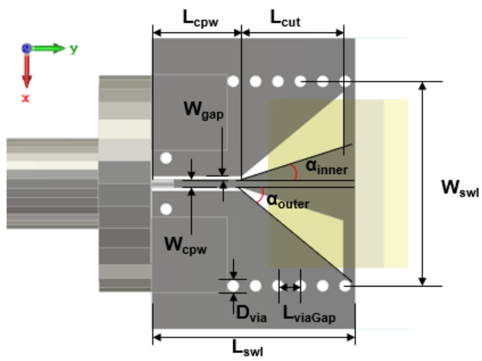


(d)

Fig. 2. The geometry of the CEW surface ware fluid antenna.

(a) side view, (b) top view, (c) back view and (d) the PCB surface wave launcher details. Dimensions: $H_{substrate}$ = 0.8 mm; $H_{container}$ = 2.0 mm; α_{inner} = 20 °; α_{outer} = 42 °; $\alpha_{container}$ = 26 °; $\alpha_{channel}$ = 30 °; $L_{container}$ = 29.0 mm; $L_{Radiator}$ = 6.5 mm; D_{via} = 0.4 mm; W_{viaGap} = 0.8 mm; D_{via} = 0.4mm; L_{start} = 6.0 mm; $L_{substrate}$ = 33.0 mm; L_{swl} = 7.0 mm; $W_{substrate}$ = 10.0 mm; W_{swl} = 7.0 mm; L_{pipe} = 17.5 mm; $L_{radiator}$ = 6.5 mm; $W_{container}$ = 5.8 mm; W_{cpw} = 0.3 mm; W_{gap} = 0.1 mm; L_{cpw} = 3.1 mm; L_{cut} = 3.5 mm; $H_{block\ gap}$ = 0.15mm; H_{block} = 0.525mm; W_{block} =1.2mm; $H_{channel}$ = 1.2mm; $W_{channel}$ = 1.2mm; $H_{pad\ connector}$ = 1.27mm; W_{pad} = 0.6mm; L_{pad} = 0.6mm; L_{blank} = 1.2mm; W_{blank} = 1.2mm.

III. Operating Principle

CEW plays a crucial role in the proposed antenna design as a method to mobilize the liquid metal. By applying a voltage to the two electrodes to create a charge redistribution on the surface of the liquid metal, and result in a change in surface tension along the length of a liquid metal submerged in the electrolyte. Marangoni forces is created along the liquid-liquid interface, that in turn produces the movement of the liquid metal in the channel [12]. However, the concentration of the electrolyte and the type of voltage supplied both affect the motion of the liquid metal in the channel. Thus, it is important to understand the effect of these parameters on their speed for using CEW in FAS. Several experiments were performed to verify the CEW implementation and the corresponding performance of liquid metals under different conditions.

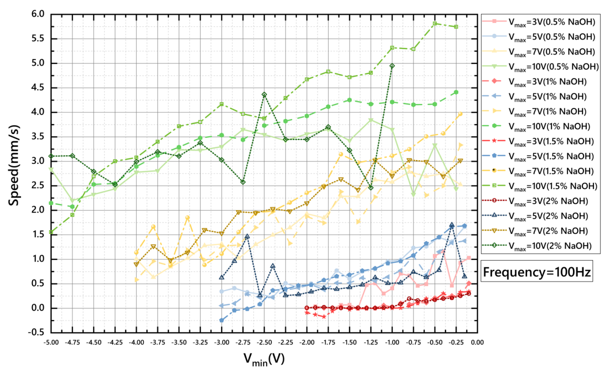
Fig. 3. The experiment setup

Fig. 3 shows the experiment setup. The silicone tube was used as the channel. Two SMA connectors was used to fix the channels onto the stripboard. Two electrodes, in the form of copper wire, were connected to a signal generator.

Experiments were performed to determine the moving speed of the liquid metal under three waveforms (Sine, Ramp, and Square) with different volume concentrations (0.5%, 1%, 1.5%, and 2%) and biasing conditions. Meanwhile, the effects of signal frequency, duty cycle and symm (the proportion of the wave greater than 0 volt in a period of the ramp wave) on speed were also measured experimentally.

IV. Measurement Results

As shown in Fig. 4, the use of CEW allows the liquid metal to shift in the channel. Moreover, the speed of movement is the fastest in the square wave among the three waveforms. Meanwhile, higher voltages and higher concentrations result in faster speed in general, but also in more speed fluctuations. Furthermore, in the case the control signal frequency, duty cycle and ramp, extreme settings will cause the fluid radiator to move slower. Therefore, a reasonable selection of parameters will play an important role in controlling its moving speed.



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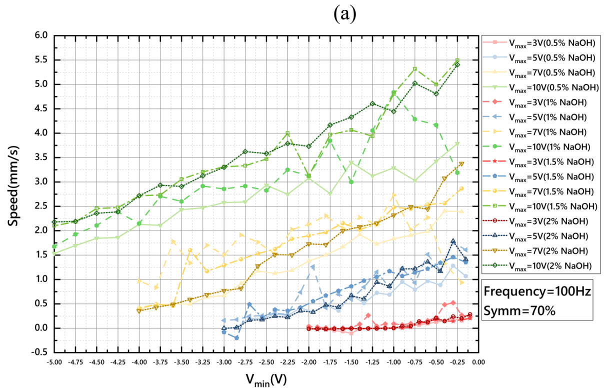

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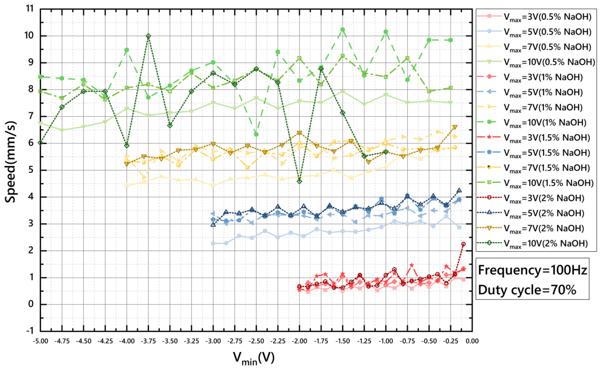

(c)

Fig. 4. (a) Sin VS. Speed, (b) Ramp VS. Speed, (c) Squ VS. Speed

V. SIMULATED RESULTS

To consider the potential impact of the electrolyte and electrode on the antenna performances, the electrolyte and two biasing pads are modelled in the simulations. The simulations for different fluid radiator position (L_{start}) are performed. It can be observed that the antenna can always maintain an operating frequency band from 23.5 to 38 GHz ($|S_{11}| < -10$ dB) when the fluid radiator position changes. It means that adding the CEW geometry (electrolyte, electrodes) will not affect the reflection coefficient of the fluid antenna in the 5G mobile communications millimetre-wave band at different fluid radiator positions.

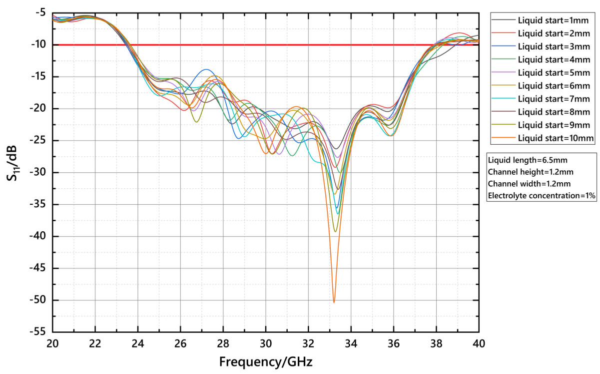

Fig. 5. S_{11} result of the antenna in different positions

Fig. 6 shows the realized gains of the fluid antenna in the yz-plane at 34 GHz at different fluid positions. It can be observed that the radiation pattern varies with the position of the fluid radiator. The maximum dynamic range of gain variation is about 27 dB at (θ, ϕ) = (85º, 90º). Moreover, the magnitude and position of the peak vary with the position of the fluid radiator.

VI. CONCLUSION

A compact continuous electrowetting fluid antenna concept has been presented. The experiment firstly demonstrate the feasibility of CEW in FAS. Secondly, the simulation results show that inclusion of the CEW geometry does not significantly affect the overall performance of the surface wave fluid antenna. Moreover, it has a wide working range that covers the Very High 5G Frequency bands, in addition to its compactness, it will be a good candidate antenna for mobile devices.

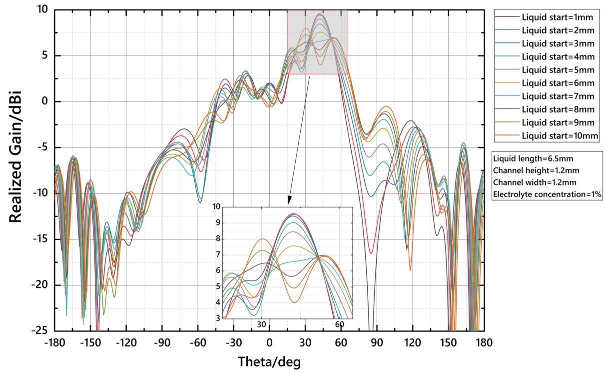

Fig. 6. The farfield radiation pattern of the antenna at 34 GHz

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