Radiation Pattern Diversified Single-Fluid-Channel Surface-Wave Antenna for Mobile Communications

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Abstract — **In this paper, an antenna design that combines surface wave and fluidic reconfigurable techniques was presented. The antenna operates in a wide frequency range from 23 to 38 GHz, which covers the Very High 5G Frequency band in the US, Europe, China, Japan, and Korea. In this design, only one RF input port is needed to achieve diversity when compared with the conventional multiple RF input ports approaches. From the simulation results, the proposed antenna design could change its radiation pattern based on the position of the fluid radiator. Such radiation pattern diversity feature can deal with channel interference issues.**

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

I. Introduction

The current mobile communications has been significantly improved by the implementation of MIMO systems. However, it is challenging to implement the MIMO system in portable devices, such as smartphones, due to the limited space available[1]. Even with the latest mobile phones equipped with MIMO systems onboard, the improvement is still limited by the predefined shapes and fixed positions of the antennas in the mobile phones. Therefore more novel antenna designs are needed to further advance present wireless communications technology[2].

Reconfigurable antennas have been proposed to improve diversity. One of the reconfigurable techniques is reconfigurable fluid antennas[3]. In fluid antennas, spatial diversity could be achieved by shifting the position of the fluid radiators[4]. 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[5]. However, to realize the proposed FAS platform, an RF feeding network with multiple output ports is usually necessary for exciting the fluid radiator at different positions[6]. Such requirements for multiple RF chains can impede the adoption of fluid antennas in a wireless system due to their high cost and complexity.

To solve the complex feeding network issue, a fluid antenna fed by a surface wave is proposed[7]. A surface wave launcher is utilized to generate the signal in the form of the surface wave propagating to the fluid radiator located on the microwave substrate. Hence the complex RF feeding network could be eliminated. Moreover, the surface wave launcher is implemented on a piece of the printed circuit board, so it can be conveniently fabricated or even be directly integrated with the main RF circuit[8].

By combining the techniques, the proposed fluid surface-wave antenna design simplifies the FAS systems and could achieve diversity gain with only one RF input port within the limited space[9],[10].

II. Antenna Geometry

The 3D view of the geometry of the proposed 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 and a K-connector.

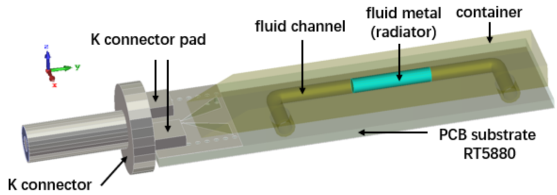
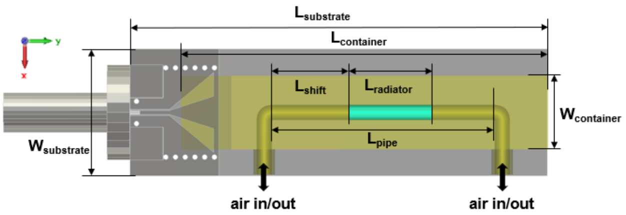


Fig. 1. The 3D view of the proposed antenna design

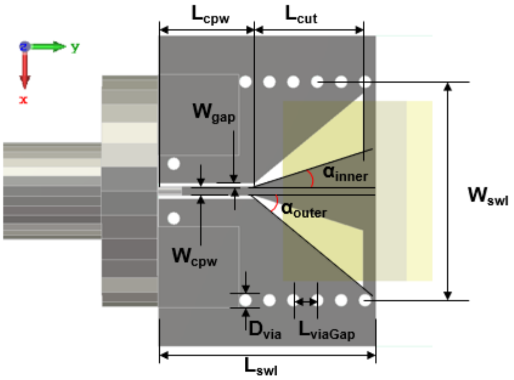
The surface wave platform of the antenna is built on a piece of Rogers RT5880 microwave dielectric substrate (ε_r = 2.2, thickness = 0.8 mm and tan δ = 0.0009 at 10 GHz), it has a ground plane on the bottom side and a surface wave launcher etched on the top side. The fluid container sitting on the top of the PCB is made of epoxy resin (ε_r = 4.0) which is 3D printed. This container includes fluid channel as well. And inside the fluid channel 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)[11]. The K-connector part is included in the model for studying the potential impact of the connector on the antenna performance, particularly, the radiation patterns.

The detail of the antenna structure can be found in Fig. 2. Two air inlets/outlets are shown in Fig. 2(b) as well. These inlets/outlets will be connected to a micropump system so that the position of the fluid radiator can be precisely adjusted. The overall dimension of the antenna structure without the K-connector is ($L_{substrate} \times W_{substrate} \times (H_{container} + H_{subsrate})$), 33 × 10 × 2.8 mm^3. The detailed dimensions have been given under the caption of Fig. 2.

(a)



(b)



(c)

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

(a) side view, (b) top view, and (c) the PCB surface wave launcher details. Dimensions: $D_{channel}$ = 1.2 mm; $H_{substrate}$ = 0.8 mm; $H_{container}$ = 2.0 mm; α_{inner} = 20 °; α_{outer} = 42 °; $\alpha_{container}$ = 26 °; $L_{container}$ = 29.0 mm; $L_{radiator}$ = 6.5 mm; D_{via} = 0.4 mm; W_{viaGap} = 0.8 mm; D_{via} = 0.4mm; L_{shift} = 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.

III. Operating Principle

The surface wave launcher is a crucial part of the proposed antenna. When the signal arrives from the K-connector, the surface wave launcher converts the signal into surface wave propagating along the positive *y*-direction on the top side of the surface wave platform. The *E*-field distribution of the surface wave is shown in Fig. 3. It shows that the surface wave launcher generates the surface wave and the wave propagates along with the platform in the *y*-direction. When the surface wave arrives at the fluid radiator, the wave will be scattered into free space. As the fluid radiator can shift along the fluid channel, it can scatter the surface wave at different positions, therefore the radiation pattern will change accordingly. When compared to the case without the fluid radiator as shown in Fig. 4(a), this scattering effect can be observed. Fig. 4(b) shows such effect on *E*-field distribution for L_{shift} = 5 mm. Consequently, radiation pattern diversity can be achieved by shifting the fluid radiator to different positions.

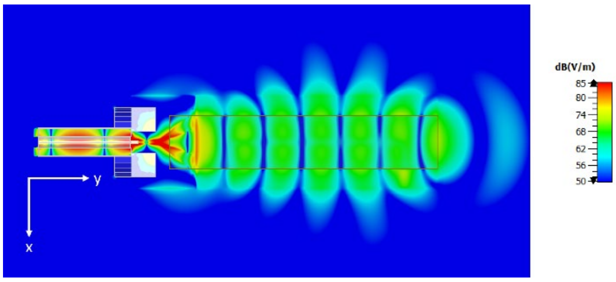
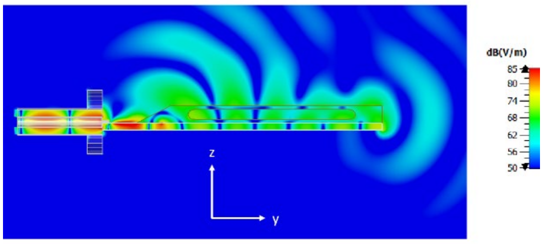
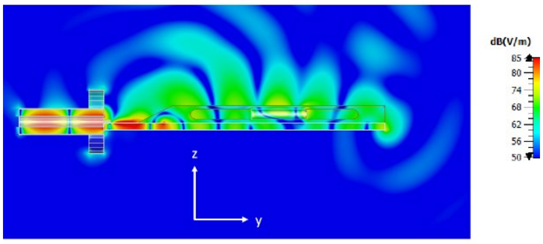


Fig. 3. 2D *E*-field distribution of the antenna at z = 0.9 mm, at 26 GHz



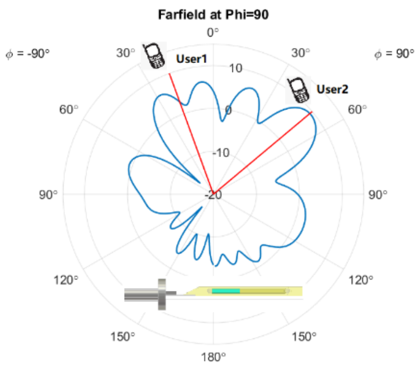
(a)



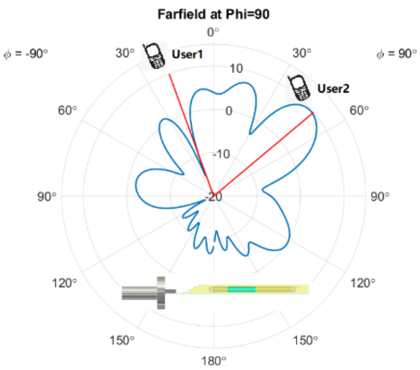
(b)

Fig. 4. *E*-field distribution (a) without radiator, (b) with radiator at L_{shift} = 5mm from side view x = 0 mm, at 26 GHz

To help the readers to visualize such feature, we provide an example. Fig. 5 shows radiation patterns of the antenna with the fluid radiator located at different positions. There are two users in this example. User 1 is located at angle (θ, ϕ) = (20º, -90º) and User 2 is at angle (50º, 90º). When establishing a reliable communication to User2, however, the signal from User 1 will also be received as shown in Fig. 5(a). Therefore, there will be huge interference. In this case, the antenna could shift the fluid radiator to L_{shift} = 3 mm. The corresponding result in Fig. 5(b) shows that the signal from User 1 is significantly reduced to a null. Thus the antenna can actively eliminates the interference.



(a) L_{shift} = 0 mm



(b) L_{shift} = 3 mm

Fig. 5. The radiation pattern comparison of the antenna with the fluid radiator at (a) L_{shift} = 0 mm L_{shift} = 3 mm at 26 GHz

IV. Simulated Results

To consider the potential effect of the connector, a K-connector is included in the simulation models. The simulations for every 1 mm step shift of L_{shift} along the 17.5 mm long channel are performed. It is observed that the antenna can always maintain an operating frequency band from 23 to 38 GHz ($|S_{11}| < -10$ dB) when the fluid radiator moves along the channel. Three of the representative S_{11} results are shown in Fig. 6. The result of the antenna without the fluid radiator is also shown for comparison. CST 2020 was used in all the electromagnetic simulations.

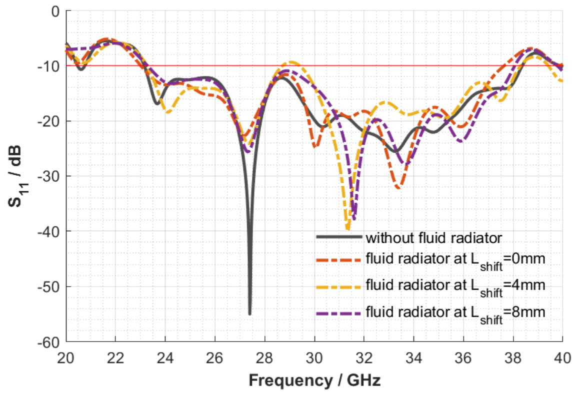


Fig. 6. S_{11} result of the antenna without a radiator and with the radiator at different positions

The radiation pattern diversity capability of the antenna can be observed from the simulation result shown in Fig. 7. The figure shows the corresponding farfield radiation patterns at 26 GHz when the fluid radiator is located at 12 different positions from $L_{shift} = 0$ mm to 11 mm. All results are shown by dotted lines with the highlight lines showing the maximum and minimum envelope of the results. The gap between the maximum and the minimum envelope is the dynamic range of the antenna can be achieved by shifting the fluid radiator. For example, the maximum and minimum realized gains the antenna could obtain at the angle $(\theta, \phi) = (45^o, 90^o)$ are around 10 dBi and 0 dBi respectively. This 10 dBi difference is the dynamic range that can be achieved by moving the fluid radiator inside the channel. The proposed antenna has a maximum dynamic range of 25.47 dB at $(34^o, 90^o)$, and has an average dynamic range of 9.07 dB across the whole 360^o.

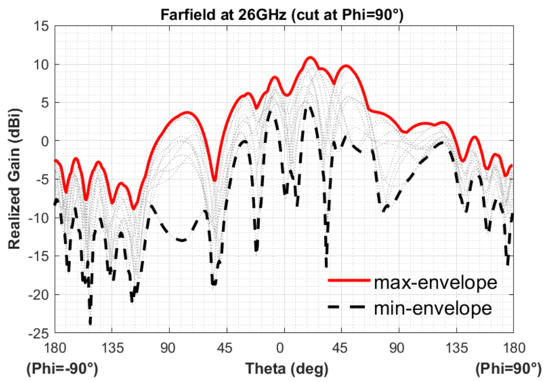


Fig. 7. The maximum and minimum envelop of the farfield radiation pattern of the antenna at 26 GHz

V. Conclusion

The proposed fluid antenna has a small physical size and simple design compared with the classic fluid antenna designs. It has a wide working range that covers Very High 5G Frequency bands. The antenna could deliver radiation pattern diversity by shifting the position of the fluid radiator. A maximum dynamic range of 25.47 dB and an average dynamic range of 9.07 dB has been achieved.

Acknowledgment

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