Liquid Metal Application for Continuously Tunable Frequency Reconfigurable Antenna

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***Abstract*— This paper presents two different designs for frequency reconfigurable antennas capable of continuous tuning. The radiator, for both antenna designs, is a microstrip patch, formed from liquid metal, contained within a microfluidic channel structure. Both patch designs are aperture fed. The microfluidic channel structures are made from polydimethylsiloxane (PDMS). The microfluidic channel structure for the first design has a meander layout and incorporates rows of posts. The simulated antenna provides a frequency tuning range of approximately 118% (i.e. 4.36 GHz) over the frequency range from 1.51 GHz to 5.87 GHz. An experimental result for the fully filled case shows a resonance at 1.49 GHz (1.3% error compared with the simulation). Experienced rheological behavior of the liquid metal necessitates microfluidic channel modifications. For that reason, we modified the channel structure used to realise the radiating patch for the second design. Straight channels are implemented in the second microfluidic device. According to simulation the design yields a frequency tuning range of about 77% (i.e. 3.28 GHz) from 2.62 GHz to 5.90 GHz.**

***Index Terms*—aperture-coupled patch antenna; continuous tuning; frequency reconfigurable; liquid metal; microfluidics.**

I. INTRODUCTION

Although several techniques have been demonstrated in literature for achieving frequency reconfigurability, most of them only support discrete tuning due to the on/off nature of switches. On the other hand, the unique properties of liquid metal offer the potential for continuous tuning, over a very wide frequency range. Moreover there are other important advantages of using liquid metal when compared with conventional techniques that will enhance the overall system performance, including: improved linearity, higher power handling capacity, and lower overall power losses/consumption.

A number of frequency reconfigurable microstrip patch antennas have been presented in the literature. In [1-2], liquid metal is used as switches to reconfigure the operating frequency of an antenna between two discrete values. In [3] a tuning range from 1.85 GHz to 2.07 GHz is demonstrated. The antenna design incorporates a U-shaped slot in the ground plane. The length of the current path, and hence operating frequency, is altered by partially filling the slot with liquid metal. A mechanically stretchable antenna is presented in [4]. The antenna is formed from liquid metal and embedded within a silicon substrate. The operating frequency of the antenna can be varied from 1.3 GHz to 3 GHz. Although [4] demonstrates continuous tuning, it suffers from poor impedance matching (S_{11} < -6 dB) over the frequency tuning range.

This paper describes two designs for continuously frequency tunable antennas based on liquid metal. The paper is structured as follows. Section II describes the structure of the two antenna designs. Section III presents and discusses simulation and measurement. Finally, conclusions are drawn in Section IV.

II. ANTENNA STRUCTURE

Fig. 1 shows the structure of the two novel antenna designs reported here. Fig. 1(a) shows the metal and dielectric stack-up used for both designs. There are three metal layers: 1) the EGaIn radiator, 2) the ground plane incorporating an aperture (W_A = 16 mm, L_A = 1.6 mm), 3) the microstrip feedline (W_F = 0.9 mm) and matching stub (L_S = 10 mm). The EGaIn is contained within a microfluidic channel structure which is contained within a 1.6 mm-thick slab of PDMS (ε_r = 2.67 and $\tan\delta$ = 0.02 and h_m = 1.6 mm). The channel structure has the following dimensions W_R = 45.7 mm, L_R = 57.1 mm and h_P = 1.0 mm, and channel height = 100 um. There are two dielectric layers: 1) the antenna substrate, and 2) the feed substrate. The antenna substrate is made from Rogers RT5880 (ε_r = 2.2, $\tan\delta$ = 0.0009 and h_A = 0.8 mm). The feed substrate is made from Taconic RF-60A (ε_r = 6.15, $\tan\delta$ = 0.0028 and h_F = 0.635 mm). The overall size of both antennas is W = 78 mm by L = 100 mm.

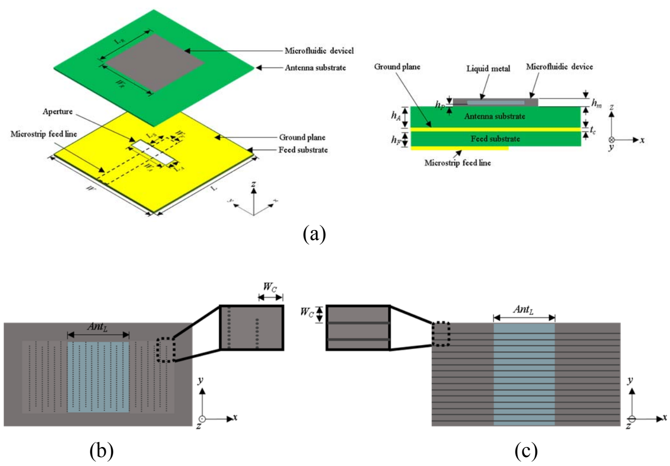


Fig. 1. Structure of the two antenna designs: (a) feed and radiator position used in both designs; (b) Design #1; (c) Design #2. Dimensions not to scale.

In both antenna designs the radiator is formed from eutectic gallium indium alloy (EGaIn) liquid metal contained within the polydimethylsiloxane (PDMS) microfluidic channel structure. The electrical length of the antenna, and hence its operating frequency, is varied by altering the amount of EGaIn within the channel (Ant_L). Inlet/outlet connectors are incorporated to facilitate insertion and removal of the EGaIn. A carrier liquid, if needed, can be used to help moving the EGaIn around within the microfluidic channel structure and prevent oxidization. Fig. 1(b) shows the structure of Design #1. This design incorporates a meander microfluidic channel structure defined by rows of posts. The posts serve two functions, namely: to guide the liquid metal and give structural support. Based on the Laplace barriers concept [5-6], the post's diameter and separation, channel segment width (W_C) and height determine the required pressure to drive liquid metal either through the channel segment or between the posts. In other words, the EGaIn should initially flow through the meandered path. Subsequently, by increasing the applied pressure, the EGaIn should be caused to flow between the posts in order to create a solid sheet of material. In Design #1 a carrier liquid is required to help move the EGaIn from the inlet point to desired location.

In order to address some practical reasons, discussed in the results section we devised a second design (Design #2). Specifically, the microfluidic channel structure is simplified. Fig. 1(c) shows the structure of the Design #2. The microfluidic channels within this antenna are straight. Each channel has a width of W_C and runs parallel to the XZ-plane. These channel segments are isolated from each other by solid PDMS walls. Carrier liquid is not needed in this design as the liquid metal is injected/withdrawn at the center of the structure via a tubing manifold.

Both designs incorporate an aperture fed microstrip patch radiator. This feeding technique allows more freedom when selecting substrate materials for the antenna and its feed. This feeding approach avoids direct contact between EGaIn and copper, which is more attractive both from chemical and microfluidic perspective because EGaIn reacts with common metals, and ensures a more mechanically reliable and hermetically sealed structure.

For Design #1 and Design #2 the width of each segment of the channel (W_C) is 1 mm and 2 mm, respectively. For Design #1 the post diameter is 100 um and the inter-post gap is 50 um. For Design #2 the wall thickness is 2 mm.

III. RESULTS AND DISCUSSION

The geometry of Design #1 is similar that presented in [7]. However the dimensions and frequency response differ. Specifically Design #1 antenna covers the sub-6 GHz band including the newly introduced 5G spectrum. These sub-6 GHz bands are most likely for part of the first phase of the rollout of 5G mobile networks deployment [8]. We simulated the effect of varying the value of Ant_L from 6.6 mm to 57.1 mm. This dimension change causes continuous frequency tuning from 1.51 GH to 5.87 GHz. This represents a frequency tuning range of 4.36 GHz (i.e. 118%). The fabricated antenna is depicted in Fig. 2 for the case where the channel is fully filled with EGaIn, i.e. Ant_L = 57.1 mm. Fig. 3 compares the simulated and measured frequency response of the antenna for this case. In the simulation result the resonance is located at a frequency of 1.51 GHz (S_{11} = -11.4 dB) whilst in the measurement result it is located at 1.49 GHz (S_{11} = -11.3 dB). The two results are therefore in good agreement with an error of only 1.3%. Simulated and measured radiation patterns (realized gain) corresponding to Ant_L = 57.1 mm are shown in Fig. 4. The variations in the radiation pattern between simulation and measurement are minor. At the resonant frequency (1.51 GHz) the antenna has a simulated realized gain of 3 dB corresponding to a total efficiency of 42%. The dimensions of the coupling aperture and matching stub for the antenna are optimized for the centre of the tuning band. At the upper and lower end of the band the matching degrades. This explains the observed reduction in gain, compared to a conventional patch antenna, at the lower end of the tuning band. We have yet to experiment with other Ant_L values and the use of a carrier liquid. In this paper we have experimentally demonstrated the fully filled tuning case for Design #1. Although, from a rheological perspective this is the simplest case, we experienced challenges. More specifically the flow behavior of this non-Newtonian fluid between posts should be further investigated. Furthermore the need for a carrier liquid adds additional complexity to Design #1 but such a liquid is not required for Design #2.

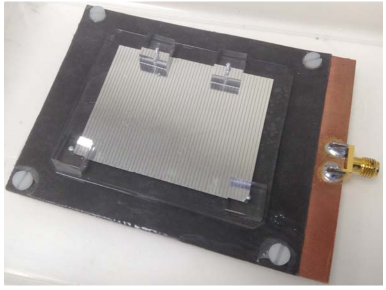


Fig. 2. Fabricated antenna of Design #1 showing a fully filled case (i.e. Ant_L = 57.1 mm).

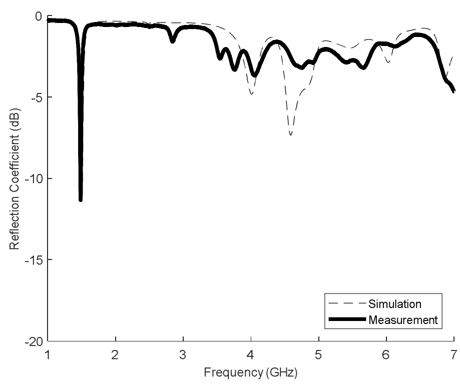
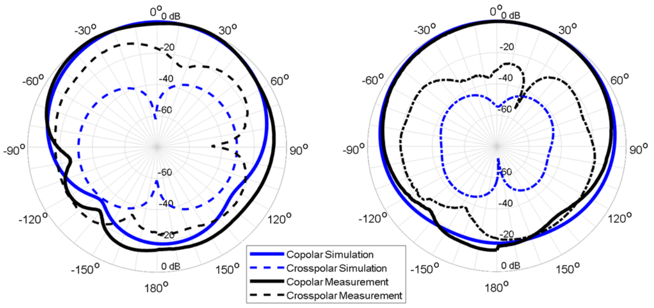


Fig. 3. Simulated and measured frequency response of the fully filled Design #1 antenna (i.e. Ant_L = 57.1 mm).



(a) (b)

Fig. 4. Radiation patterns (realized gain) comparsion between simulation and measurement of the fully filled (i.e. $Ant_L = 57.1$ mm) Design #1 antenna: (a) E-plane ($\varphi = 0°$); (*b*) H-plane ($\varphi = 90°$).

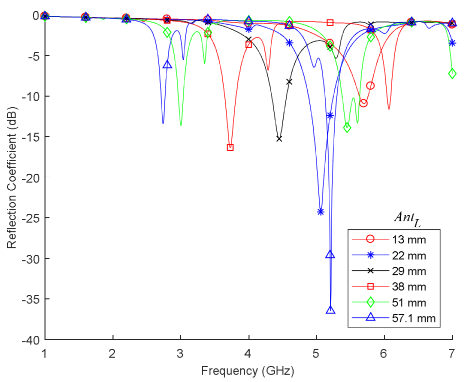


Fig. 5. Simulated frequency response of Design #2 antenna when varying Ant_L.

A second design (Design #2) is developed to overcome the limitations discussed above. Fig. 5 shows the simulated frequency response of Design #2 for some selected values of Ant_L ranging from 13 mm to 57.1 mm. The reader is reminded that the design and dimensions of the feeding structure for this antenna are the same as those for Design #1. That is to say they have not been re-optimized for this design. Design #2 provides continuous frequency tuning from 2.62 GHz to 5.90 GHz. This equates to a tuning range of about 77% (i.e. 3.28 GHz).

IV. Conclusion

The paper presents two different microfluidic designs enabling continuous frequency tuning over sub-6 GHz 5G bands. The radiator is formed entirely from liquid metal. Design #1 provides tuning from 1.51 GHz to 5.87 GHz (i.e. 4.36 GHz or 118%). Design #2 provides a frequency tuning from 2.62 GHz to 5.90 GHz (i.e. 3.28 GHz or 77%). The structure and dimensions of the feed network used in both designs are identical.

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