A Reconfigurable MIMO Handset Antenna Employing Liquid Metal

Haiqiang Gao¹, James Kelly², Xue Zhang¹ and Zhengpeng Wang¹a)

Abstract This paper presents a reconfigurable MIMO handset antenna based on liquid metal. The antenna covers the eight frequency bands of the LTE-A standard. This antenna comprises: a monopole element, a IFA element, and a dual-purpose L-shaped branch which is connected to the ground plane. The function of the L-shaped branch is to improve the isolation, within the low frequency band (698-960MHz), between two elements. A strip of liquid metal which connects to the arm of the IFA, coordinated with the L-shaped branch, can be used to alter its resonant frequency. The operating principle of this strip is analysed using an equivalent capacitor model. The theory of characteristic mode is used to analyze the properties of proposed antenna. To validate the concept, a prototype antenna with size of 120×60×0.8 mm³ was fabricated and measured.

key words: multiple-input multiple-output (MIMO), reconfigurable mobile handset antenna, liquid metal, characteristic mode analysis
Classification: Microwave and millimeter wave devices, circuits, and hardware

1. Introduction

Mobile handsets are now an indispensable feature of modern life, and the demands for higher transmission rates are increasing [1, 2, 3]. Multiple input multiple output (MIMO) is a promising technology that can significantly improve the performance of wireless communication systems. In fact, MIMO technology has already been widely used within the base station antennas of mobile networks. Nevertheless, it is more challenging to deploy this technology in mobile handsets because the volume constraints result in severe mutual coupling [4, 5]. The latest studies into MIMO handset antennas have tended to concentrate on frequency bands above 1GHz [6, 7, 8, 9, 10], where it is easier to achieve effective decoupling compared with the situation in the frequency bands below 1GHz. A key reason for this is that the wavelength is longer at lower frequencies and so radiating elements must be separated by larger distances in order to preserve the same electrical separation distance. The longer wavelength also leads to larger decoupling structures [11]. Moreover, in the low frequency band, the ground plane becomes the main radiator, and is shared by multiple antennas. This leads to difficulties in achieving angular and polarization diversity.

Reconfigurable antennas normally provide better performance in terms of bandwidth, realized gain and port-to-port isolation, than their fixed counterparts [12, 13]. However, commercial tuning elements such as PIN and varactor diodes introduce non-linearities and require complex biasing networks. Those biasing networks can affect the radiating performance of the antenna. The first reconfigurable antenna based on liquid metal was proposed in 2009 [14]. Later, a liquid metal-based patch antenna, monopole antenna and Yagi antenna were proposed [15, 16, 17, 18, 19]. Liquid metal offers several significant advantages, in comparison, with conventional switching and tuning techniques, including: 1) reduced complexity of biasing and control circuits, 2) reduced overall power consumption, 3) improved linear performance, and 4) enhanced tuning range [20, 21, 22]. The main disadvantage of using liquid metal for tuning antenna performance is the low tuning speed. Additionally, the structure of the channel may have an impact on the antenna performance.

The theory of characteristic modes provides valuable insight which can be used to help optimize the design of MIMO antennas [23, 24]. This can be achieved by: 1) taking advantage of orthogonal characteristic modes, 2) by exciting different modes or modes with special phase relationships, 3) enhancing the isolation between radiating elements [25, 26].

In this letter, we propose a reconfigurable MIMO antenna based on liquid metal. The antenna is designed for using within a mobile handset and consists of a modified Inverted-F Antenna (IFA) and a monopole antenna [27, 28, 29]. The operating frequency of the IFA antenna can be tuned with the aid of a strip of liquid metal [30]. The proposed antenna is planar, and has the advantage of low cost and low manufacturing complexity.

2. Antenna configuration

Fig.1 illustrates the geometry of the proposed two elements MIMO antenna. The first radiating element, connected to port 1, is a modified Inverted-F Antenna (IFA). The second element, connected to port 2, is a monopole. In the proposed antenna the monopole serves as the main

¹School of Electronic & Information Engineering, Beihang University, Beijing, China
²School of Electronic Engineering and Computer Science, Queen Mary University of London, Mile End Road, London, E1 4NS, U.K.
a) wangzp@buaa.edu.cn

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radiator and covers the entire working frequency band (i.e. 698MHz to 960MHz and 1710MHz to 2690 MHz). The IFA serves as an assistant antenna, whose resonant frequency can be tuned. The radiating part of the IFA is orientated horizontally in Fig.1(b), the end of this radiator is split into 6 different sections. A slug of liquid metal, located in the fluidic channel above the PCB, is used as a switch to bridge the gaps between those sections and thus tune the operating frequency of the antenna. In this way we can vary the length of the IFA (from 30mm to 60mm) and thus tune its operating frequency from 698 MHz to 960 MHz. This tuning range covers the following important mobile bands: LTE700/GSM850/GSM900. The instantaneous operating bandwidth of the antenna is 30MHz. For the purpose of the study, reported here, we employed a commercially available liquid metal called Galinstan. This material is formed from an alloy of Gallium. Fig.2 shows a photograph of a hardware prototype, that was fabricated in order to validate the design. In the hardware prototype the liquid metal channel is formed within a slab of polymethyl methacrylate (PMMA), also known as acrylic, as shown in Fig.2(a). PMMA has a relative permittivity of 3.7. The PMMA slab was glued to the substrate material and occupies a volume of $32 \times 14 \times 3 \text{mm}^3$. In the measurement, a syringe is used to control the liquid metal strip, which is connected to the channel through a pipe, the liquid metal is injected into and absorbed from the channel from the left side of the channel.

Fig. 1 Geometry of (a) proposed liquid metal based reconfigurable MIMO antenna. (b) IFA element. (c) monopole element.

Branch 1 and branch 2 are located on the same metal layer as the ground plane. Branch 1 was introduced to ensure that the IFA element operates throughout the high frequency bands (from 1.7 GHz to 2.7 GHz), including DCS/PCS/UMTS/LTE2300/LTE2500. It is located close to port 1, has a length of 23mm, and resonates at around 2700MHz. In order to tune the operating frequency of the IFA, connected to port 1, we discovered that it was first necessary to reduce the mutual coupling between the two radiating elements of the MIMO antenna. Branch 2 was introduced in order to perform this function and it has the effect of improving the isolation from about 5 dB to more than 10 dB. Having successfully decoupled the two antennas it is possible to tune the operating frequency of the IFA antenna, by varying its length with the aid of liquid metal. An alternative way of viewing this situation is to consider the equivalent capacitance between the IFA and the ground plane, as shown in Fig.3.

Fig. 2 Photo of proposed liquid metal based reconfigurable MIMO antenna. (a) front side. (b) back side.

Fig. 3 Equivalent capacitance between the IFA and the ground plane.
If we were able to tune this equivalent capacitance, then we would be able to alter the resonant frequency of the IFA. Unfortunately, this is not possible because the horizontal arm of the IFA is located too far away from the ground plane. Introducing branch 2 has the effect of extending the ground plane so that it is now closer to the IFA. This increases the capacitance between the IFA and the ground plane and allows us to tune the IFA.

3. Results and discussion

The performance of the hardware prototype, depicted in Fig.2, was determined via microwave measurement using a vector network analyzer N8363B. Fig.4 shows the simulated S-parameters of the proposed MIMO antenna. The simulation results were obtained using CST Microwave Studio 2017.

Fig. 4 Simulated s-parameters of the proposed antenna with liquid strip length of (a) 5mm. (b) 15mm. (c) 25mm.

The length of the IFA strip was varied between 3 discrete values, namely: 5mm, 15mm, and 25mm. The 6 dB return loss bandwidth of the monopole covers the entire working frequency band (i.e. 698MHz to 960MHz and 1710MHz to 2690 MHz). The presence of branch 2 enables an isolation of at least 10 dB to be achieved, between the two antenna elements, over the entire operating frequency band. From the simulation results we can see that altering the length of the IFA strip has almost no effect on the S_{22} performance of the monopole element.

Fig. 5. Measured S-parameters with different IFA strip lengths.

Fig.5 shows the measured S-parameter performance of the antenna corresponding to different lengths of the IFA strip. In the measurements, liquid metal was used to tune the operating frequency of IFA within the low frequency bands. Normal saline was also tried and yield similar results, to those described above. The measured results reveal that the proposed technique for frequency tuning yields good performance. The measured S_{12} remains below -10 dB throughout the entire operating frequency bands, irrespective of the length of the IFA. The measured S_{22} remains almost unchanged as the length of the IFA is varied, thus validating the results obtained through simulation. The measured results are in good agreement with those obtained through simulation. Introducing the PMMA channel, affects the resonant frequency in low frequency bands. However, the impact is limited.

Fig.6 shows the simulated 3D radiation patterns, corresponding to the IFA tuning strip having a length of 15mm which corresponds to an operating frequency of 845MHz is the resonant frequency of IFA element in low frequency bands, in high frequency bands, 2300MHz is taken for example. The efficiency of the proposed antenna was determined through computer simulation. Table I gives the total radiation efficiency corresponding to different lengths of the IFA strip that enable tuning within the low frequency bands. Within the high frequency bands, the total radiation efficiency is in excess of 90% and not shown for simplicity. The efficiency values are adequate for mobile handset applications.

Table 1 Simulated radiation efficiency

| Liquid Metal Length/mm | Center Frequency/MHz | Efficiency of IFA/% | Efficiency of Monopole/% |
|------------------------|----------------------|---------------------|-------------------------|
| 5                      | 947.5                | 86.0                | 87.1                    |
| 15                     | 845.0                | 71.1                | 82.5                    |
| 25                     | 762.5                | 58.9                | 84.5                    |

Fig.7 shows the simulated surface current distribution,
associated with the proposed antenna with and without branch 2 present.

![Simulated surface currents](image1)

Fig. 7. Simulated surface currents. (a) without branch 2. (b) with branch 2.

The distributions were obtained by exciting the antenna from port 2. When branch 2 is absent (Fig. 7(a)) we observe that there is an increased level of surface current on the IFA. The concentration of current, on the IFA is reduced when branch 2 is introduced (see Fig.7(b)). This implies that the isolation between the two antennas is improved by the introduction of branch 2.

![Eigenvalues](image2)

Fig. 8. Eigenvalues of proposed antenna.

Finally, the theory of characteristic modes was used to study the antenna and help to explain why addition of branch 2 improves the isolation, between two radiating elements (i.e. the IFA and monopole). The eigenvalues are shown in Fig.8, only five modes need to be considered as the eigenvalues of other modes are too large in the eight frequency bands. Based on the characteristic mode analysis we can see that, for mode 1, the majority of the current is concentrated on the planar monopole and there is relatively little current on the IFA, as shown in Fig.9(a). For mode 2, by contrast, the majority of the current is concentrated on the IFA and there is relatively little current on the planar monopole, as shown in Fig.9(b). Mode 1 and mode 2 are orthogonal to one another. If we were able to excite these modes, in a very pure sense, then we would observe high isolation between the radiators. At low frequencies mode 1 is dominant, as the frequency increases modes 1 and 2 become more similar in strength.

![Modal currents](image3)

Fig. 9. Modal currents at 845MHz. (a) mode 1. (b) mode 2.

4. Conclusion

A liquid metal based reconfigurable MIMO planar antenna that is capable of multiband operation in the mobile handsets is presented in this paper. This MIMO antenna is composed of a IFA element and a monopole element, high radiation efficiency and good isolation is achieved. The proposed MIMO antenna has been fabricated and measured according to design parameters, simulated and measured results agree well. The introduction of liquid metal allows the length of the radiating strip of the IFA to be varied, thus affecting its operating frequency. The L-shaped branch2 together with IFA strip is equivalent to a capacitor between the radiating strip of IFA and the ground plane. The resonant frequency of the IFA can be tuned, throughout the low frequency band, using this capacitor. The L-shaped branch2 also improves the isolation between the 2 antennas to better than 10 dB. An analysis, based on the theory of characteristic mode, shows that two elements are associated with different modes throughout the entire working frequency bands. High isolation is provided by virtue of the orthogonality between the characteristic modes.

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