

Package-in-Dielectric Liquid Patch Antenna Based on Liquid Metal Alloy

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Abstract—A fully dielectric packaged liquid patch antenna based on liquid metal alloy is presented. In this work, there are two hollow cavities embedded in a dielectric box, including a rectangular cavity placed at the upper portion acting as the radiating element, and a non-planar cavity with a central groove under the radiating element serving as the ground plane. The antenna is realized by 3D printing technique, alleviating assembly tolerance and uncertainties from printed-circuit-board approach which would degrade antenna performance. The radiating element and the ground plane are fully metallized by filling liquid metal alloy. Unlike traditional liquid antennas, the liquid packaging antenna is completely metallized by conductive liquids which does not contain any solid metals. The proposed antenna is designed to operate at 5.2 GHz. Results show that the proposed liquid patch antenna produces a satisfactory impedance matching, and a good agreement between simulation and measurement in terms of radiation characteristics is achieved at the desired frequency.

Index Terms—3D printing, conductive liquid, EGaIn, liquid metal alloy, package-in-dielectric.

I. INTRODUCTION

Liquid antenna is a research hotspot in recent years. The liquid antenna has many advantages compared with traditional solid metal antennas, such as easy to achieve reconfigurable performance, feasibility to conform with various shapes and low cost. Currently, many types of liquid antennas have been reported. On one hand, from a perspective of liquid materials adopted for the antennas, water-based antennas [1]-[4], liquid metal antennas [5] and water-mixture antennas [6] are found in literatures. On the other hand, from a perspective of antenna performances, there are frequency reconfigurable antennas [7],

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pattern reconfigurable antennas [8], [9] polarization reconfigurable antennas [10]-[12], and gain tunable antennas [13]. Most of the above-mentioned liquid antennas are realized through a complicated assembly process, i.e., the antennas are disassembled into several separate parts first, and then each part is manufactured by machining or 3D printing technique independently. This non-monolithic processing and reassembly approach is time-consuming and costly, as well as introducing more factors affecting antenna performance, which limits the practical application of the liquid antennas.

In order to alleviate the above complex processing problems, liquid packaging antenna is proposed in this work. The proposed liquid packaging antenna is a kind of liquid metallized antenna. Unlike the traditional liquid antennas [1]-[13], the liquid packaging antenna is completely metallized by conductive liquids which does not contain any solid metals other than the feeding probe, and is fully packaged by dielectric materials. Recently, antenna-in-package (AiP) technology attracts lots of investigation in various applications [14]-[21], but little attention has been paid to the integration and package of liquid antennas.

In this paper, package-in-dielectric (PiD) liquid patch antenna rested on gallium-based liquid metal alloy EGaIn ($\sigma=5.1\times 10^6$ S/m with a melting point of 11.3 °C) is investigated, designed, and verified by experimental results. The proposed liquid packaging antenna is designed to operate at 5.2 GHz. Both simulated and measured results show that the liquid patch antenna can achieve a good impedance matching and acceptable radiation characteristics at the desired frequency.

II. ANTENNA STRUCTURE AND CONFIGURATION

The configuration of the proposed liquid patch antenna is shown in Fig. 1. A T-shaped dielectric box is printed by using a ZRAPID Stereo Lithography Appearance (SLA) printer [22]. The printer enables printing photopolymer resin with a layer thickness precision of about 0.02 mm. As the properties of the used photopolymer resin at high frequencies are unknown, its dielectric constant and loss tangent are measured in advance through an in-house dielectric assessment kit (DAK) [23], the measurement setup of which is shown in Fig. 2. In this work, the dielectric constant and the loss tangent of the selected photopolymer resin are about 2.7 and 0.005 respectively, which is also tasteless and non-toxic, and especially suitable for bio-medical engineering and industrial applications.

There are two cavities inside the T-shaped dielectric box. The upper cavity is a rectangular cavity, which forms the radiating patch; while the bottom cavity is a non-planar cavity with a central groove, which constitutes the ground plane. The antenna is finally fed by a coaxial SMA connector. The inner

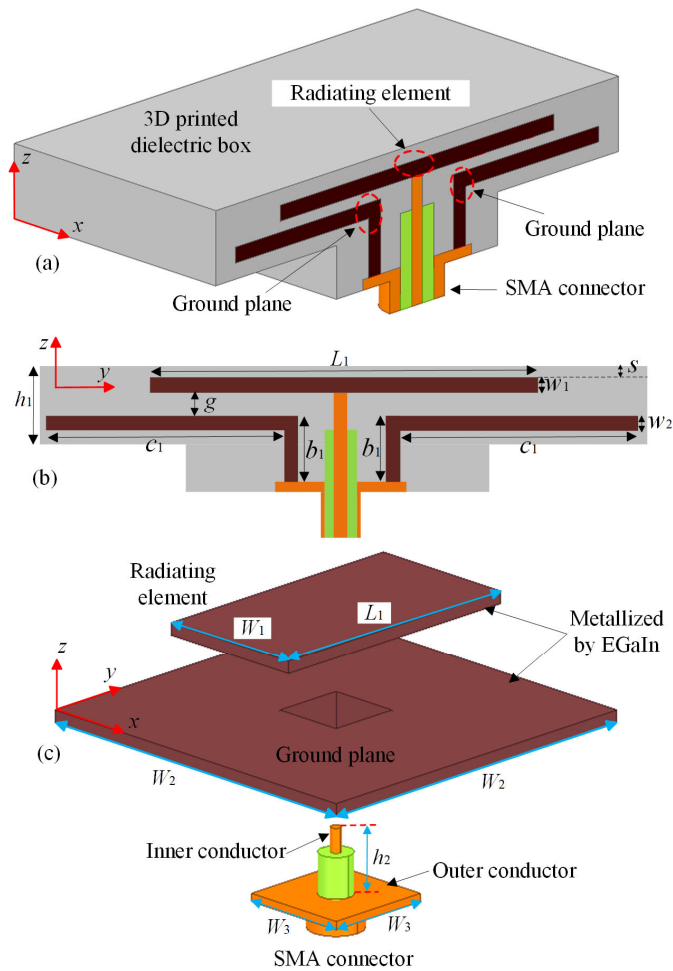


Fig. 1. Configuration of the proposed liquid patch antenna (a) vertical 3-D cross-sectional view, (b) vertical 2-D cross-sectional view, (c) exploded view without the dielectric box.

conductor of the SMA connector is inserted in the T-shaped dielectric box and completely contacted with the upper radiating patch, while the outer conductor is connected to the ground plane. It is worth mentioning that the SMA connector is wrapped by a layer of insulating material (green color shown in Fig. 1), which is able to further prevent the liquid metal alloy inside the upper radiating patch from leaking to the ground plane. Fig. 1(a) and (b) show the vertical 3-D cross-sectional view and vertical 2-D cross-sectional view of the proposed antenna, respectively. Fig. 1(c) exhibits the exploded view of the liquid patch antenna without the T-shaped dielectric box.

The radiating patch and the ground plane are obtained by metallizing the two cavities with filling liquid conductive material (EGaIn). There are many liquid conductive materials with good conductive property available in markets. Carbon nanotube pastes, graphene solutions, saline water are aqueous mixtures with high conductivity, but they are easily to exhibit dispersive phenomenon and energy absorption characteristic. Though mercury is a good conductive liquid with a low melting point that can be used for designing RF devices, it is harmful to human body as well as the environment. Recently, it is found that the Ga-based eutectic alloys, such as EGaIn, EGaSn, and EGaInSn, show tunable melting temperatures from $-19\text{ }^{\circ}\text{C}$ to far above room temperature, depending upon their composition

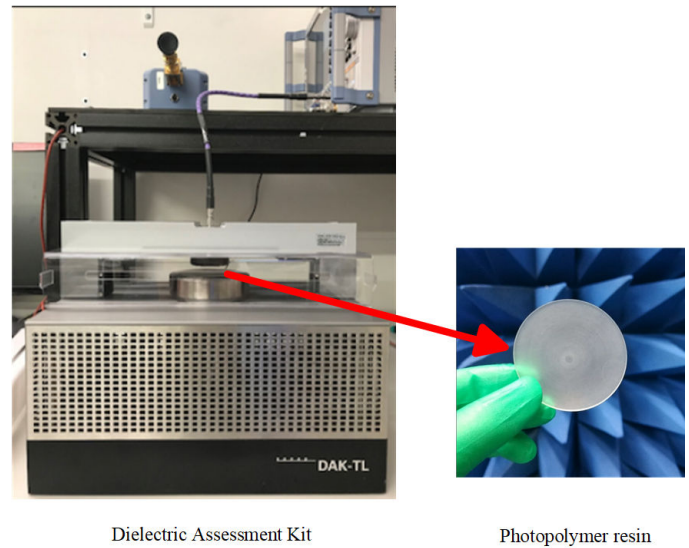


Fig. 2. Photos of Dielectric Assessment Kit and photopolymer resin.

[24]. Furthermore, the Ga-based eutectic alloy has the characteristics of environmental-friendly, low-cost, and reliable properties, which is a good candidate for designing flexible and reconfigurable RF devices [25], [26].

III. SIMULATION AND ANALYSIS

The liquid conductive material used in this work is a kind of Ga-based eutectic alloy (EGaIn), with high conductivity of $\sigma=5.1\times 10^6\text{ S/m}$ and a low melting point of $11.3\text{ }^{\circ}\text{C}$. The EGaIn has stable fluidity when the temperature is larger than its melting point, and it can be stored with plastic bottles due to its non-corrosive property. Numerical simulations are conducted by using the electromagnetic simulator CST Microwave Studio. The proposed liquid antenna is designed at the frequency of 5.2 GHz, which is suitable to operate in WLAN band for indoor communication. The major dimensional parameters of the proposed antenna are listed as follows: $L_1=32\text{ mm}$, $W_1=18.8\text{ mm}$, $W_2=45\text{ mm}$, $W_3=12.7\text{ mm}$, $w_1=w_2=1.5\text{ mm}$, $b_1=7\text{ mm}$, $c_1=18\text{ mm}$, $h_1=6\text{ mm}$, $h_2=9\text{ mm}$, $g=2\text{ mm}$, $s=1.5\text{ mm}$.

The working mechanism of the proposed liquid packaged antenna (seen in Fig. 1) is similar to the conventional bottom-fed microstrip antenna, but the significant difference between the liquid packaged antenna and the traditional solid metal microstrip antenna is that the former must be fully wrapped by dielectric material due to the fluidity feature of the liquid metal alloy. Therefore, the effect of the dielectric layer on the antenna performance is worth studying, especially the thickness of the top dielectric layer (thickness: s). The electrical performances in terms of resonant frequency and radiation efficiency are investigated under various physical configurations of the top dielectric layer.

Fig. 3 shows the reflection coefficient of the proposed antenna when tuning the parameter s from 1 mm to 2 mm with a step increment of 0.5 mm. When s increases, one can observe that the central resonant frequency shifts to lower band from 5.25 GHz to 5.21 GHz. It can be understood that the thicker the top dielectric layer is, the lower the overall effective dielectric constant will be, and thus the resonant frequency becomes lower. Furthermore, the resonance depth rises at the same time

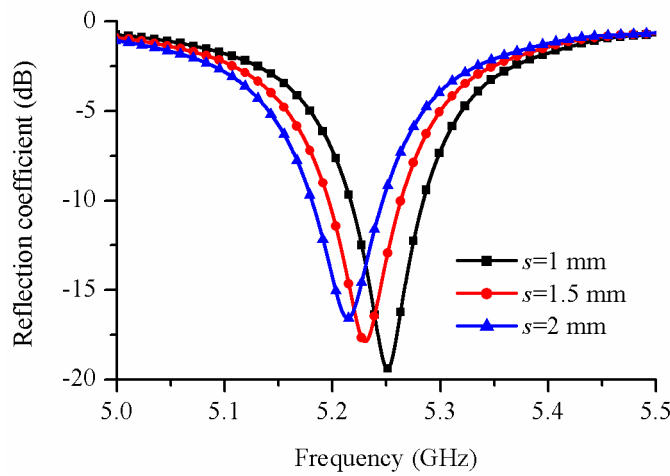


Fig. 3. Simulated reflection coefficient with various values of s .

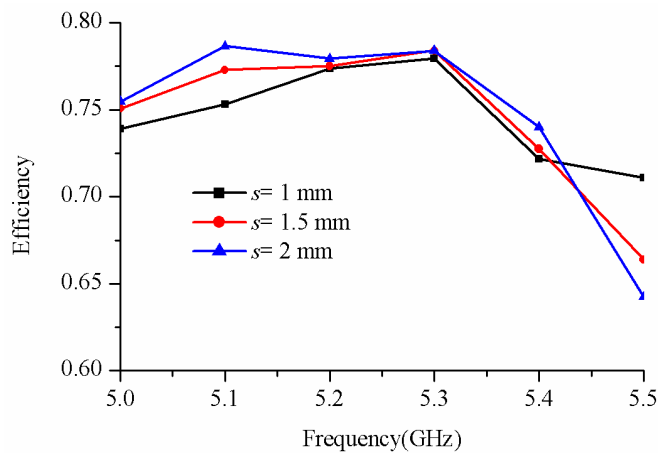


Fig. 4. Simulated radiation efficiency with various values of s .

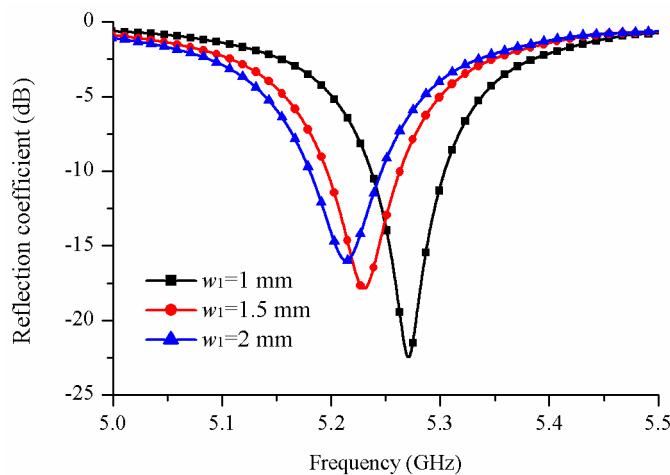


Fig. 5. Simulated reflection coefficient with various values of w_1 .

as the impedance matching is also affected by the effective dielectric constant.

Fig. 4 shows the radiation efficiency under difference values of the parameter s . It can be seen that the thickness of the top dielectric layer has little effect on the radiation efficiency. Small difference (1%) is obtained at the corresponding operational bands when s increases from 1 mm to 2 mm. Hence, a conclusion can be drawn that this dimension has certain effect

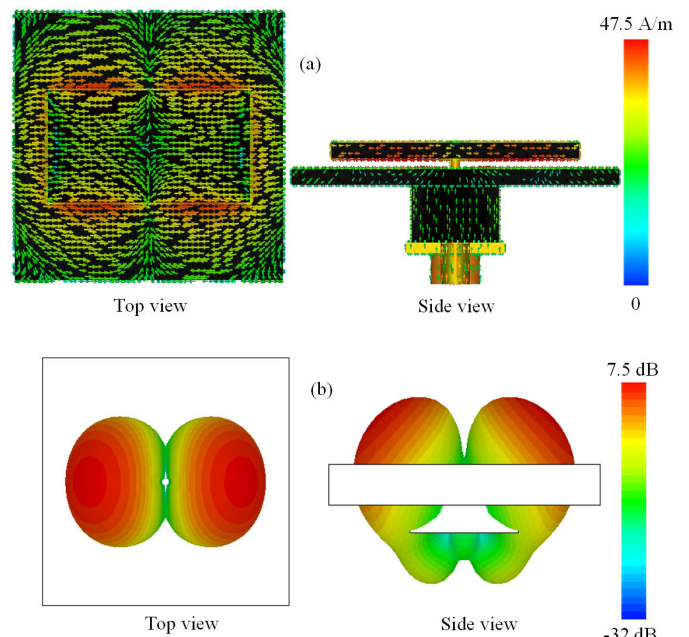


Fig. 6. Simulated (a) surface current distributions and (b) 3-D radiation patterns at 5.23 GHz.

on the reflection coefficient but limited influence on the radiation efficiency.

On the other hand, in order to obtain an operating center frequency at around 5.2 GHz, the width (W_1) and length (L_1) of the proposed radiating patch are set to 18.8 mm and 32 mm, respectively, with reference to patch antenna design methodology. In this work, the calculated length (L_1) of the radiating patch is slightly larger than a half-wavelength ($\lambda_0/2 \approx 29$ mm). As the radiating patch is metallized by the liquid metal alloy, its thickness (w_1) mainly depends on the cavity volume as well as the accuracy of the 3D printer. In order to investigate the effect of the thickness (w_1) on the antenna performance, parametric study is performed. As can be seen in Fig. 5, the resonant frequency is getting lower when w_1 is tuned from 1 mm to 2 mm with a step increment of 0.5 mm. Additionally by considering the 3D printer's accuracy and processing convenience, the thickness of the radiating patch is set to 1.5 mm.

Fig. 6 demonstrated the simulated surface current distributions and 3D radiation patterns of the proposed antenna. As presented in Fig. 6(a), high order resonance of TM_{02} mode is generated due to the specific feed position. Fig. 6(b) exhibits the corresponding radiation patterns at 5.23 GHz. One can observe that unidirectional dual-beam patterns with maximum gain of 7.5 dBi are obtained. All the simulated results demonstrate the feasibility of the proposed liquid patch antenna.

IV. FABRICATION AND MEASUREMENT

Fig. 7 shows the proposed fabricated antenna as well as the used tool (syringe) and the liquid metal alloy (EGaIn). The simplified fabrication process is illustrated in Fig. 8. The first step is to realize the T-shaped dielectric box by using an SLA printer. As afore-mentioned, there are two hollow cavities embedded in the T-shaped dielectric box: a rectangular cavity and a non-planar cavity with a central groove, which are

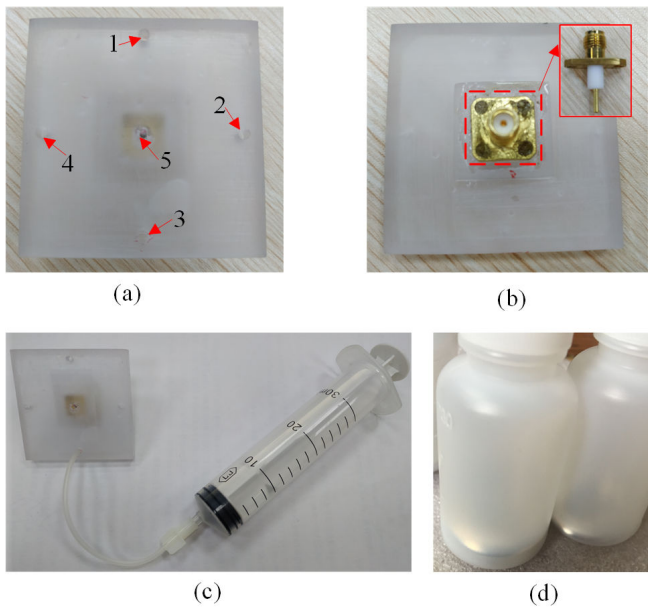


Fig. 7. Fabricated liquid antenna (a) top view and (b) back view; (c) inject liquid EGaIn into the proposed antenna by using a small syringe; (d) liquid EGaIn.

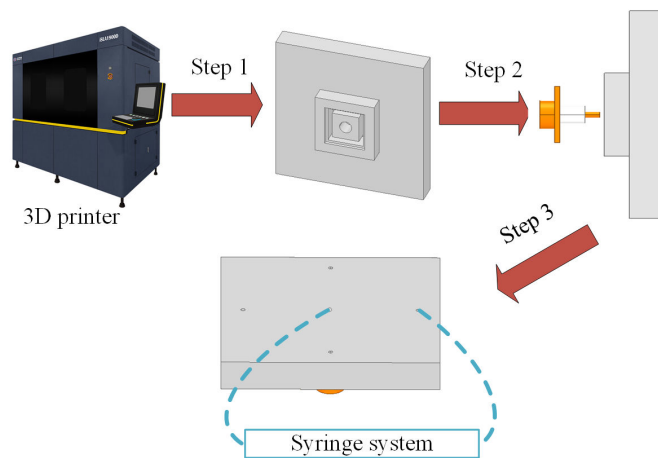


Fig. 8. Fabrication process.

metallized to form the radiating element and the ground plane respectively. In order to inject the liquid metal alloy into the two cavities, several small inlets of air holes with radius of 0.5 mm are reserved. As can be seen from Fig. 7(a), there are five air holes are drilled on the top surface of the antenna. Among them, the air holes marked with “1, 2, 3, 4” are utilized to inject the liquid EGaIn so as to metallize the non-planar cavity (ground plane); while the air hole marked with “5” is left for metallizing the rectangular plane cavity (radiating element). The second step is to install the SMA connector. The lower part of the SMA inner conductor is wrapped by a layer of insulating material (white color shown in Fig. 7(b)). The SMA connector is inserted to the dielectric box and sealed by using insulating glue. The last step is to fill the liquid EGaIn into the two cavities to form the metallized radiating element and ground plane by using syringes. When the liquid metal alloy is full filled in the planar cavity (radiating element), the radiating element is able to well contact with the SMA inner conductor. Similarly, once the liquid metal alloy is full filled in the non-planar cavity (ground plane), the ground plane can well

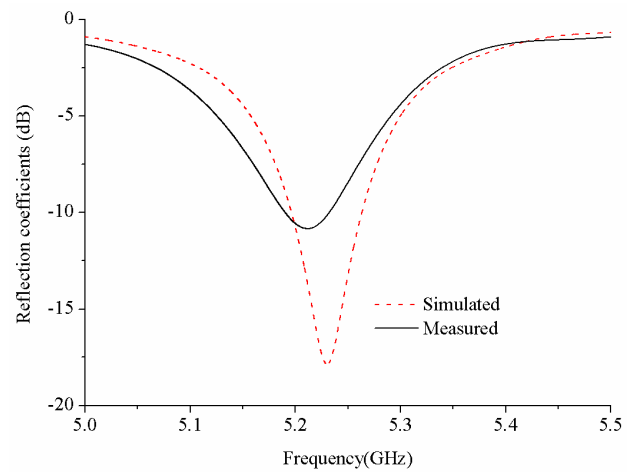


Fig. 9. Simulated and measured reflection coefficient.

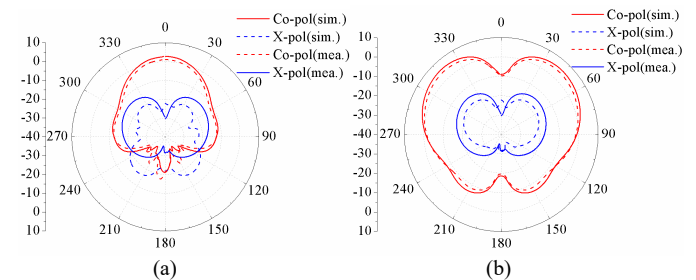


Fig. 10. Simulated and measured radiation patterns (a) xoz -plane, (b) yo z -plane.

contact with the SMA outer conductor. After the two cavities are filled with liquid EGaIn, all the inlets (air holes) are sealed with insulating glue.

The tests are conducted at room temperature about 25.2 °C. The simulated and measured reflection coefficients are shown in Fig. 9. The measured reflection coefficient has acceptable variation compared with the simulated one (shifting to lower frequency and the resonance depth rises). Fig. 10 illustrates the co-polarization (Co-pol.) and the cross-polarization (X-pol.) gain patterns of the proposed antenna at the operating frequency of 5.23 GHz. The measured (mea.) gain is a bit lower than the simulated (sim.) one. The difference between the simulation and the measurement may be traced to the tolerances caused by the manufacturing process, as well as to the manually-operated syringe which is employed to inject the liquid metal alloy into the proposed antenna. In general, the experimental results show that the proposed package-in-dielectric patch antenna exhibits a good impedance matching and acceptable radiation characteristics at the desired frequency.

V. CONCLUSION

A package-in-dielectric liquid patch antenna based on liquid metal alloy is presented. The radiating patch and ground plane of the proposed antenna are metallized by filling the liquid metal alloy EGaIn. Simulated and measured results verify that the proposed liquid patch antenna produces a satisfactory impedance matching and a good agreement of radiation characteristics at the desired frequency. This work proposes a possible approach for designing RF packaging devices by combining 3D printing technique with conductive liquids.

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