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High Performance UHF RFID Tag Antennas on Liquid-Filled Bottles

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Abstract—It is challenging to design a high-performance UHF RFID tag antenna on a liquid-filled bottle due to the high conductivity, high permittivity, and the variety of liquids. A systematic way how to design a high-performance UHF RFID tag antenna on a liquid-filled bottle is presented. A simple design consisting of a folded dipole and a loop matching structure is first proposed for a tag antenna placed on a water bottle. A co-design approach is adopted to make the water and bottle surface become a part of the tag antenna to eliminate the significant influence of the environment. The measurement results at 915 MHz show that the reading range of the simple design can reach 8 m in the absence of the water bottle and reach 4.2 m when it is placed on a water bottle. The folded dipole on the water bottle is then optimized to improve the gain significantly, and a maximum gain of −5.54 dBi is achieved at 915 MHz. Furthermore, the impedance bandwidth for the tag antenna on the water bottle is greatly improved by increasing the number of loops in the impedance matching structure from one to three, and the −6 dB impedance bandwidth of over 100 MHz (simulation) or 84 MHz (experiment) is achieved. A reading range of 5.6 m is achieved when the tag antenna is placed on a water bottle at 915 MHz.

1. INTRODUCTION

RFID (Ratio Frequency Identification) technology, which allows identifying an object or a group of objects without physical contact [1], has gained much interest recently in logistics management and IOT (internet of things) industries. The superiorities of RFID in asset tracking and SCM (Supply Chain Management) have already been widely recognized [2]. Meanwhile, unmanned retail has attracted much attention, and RFID has become one of the key technologies for its realization. In terms of the form, tags of label types are more favorable as they are low-cost, small and flexible, and can be hidden from the surface of the object for security or appearance reasons [3]. However, in practice, there are still unresolved issues related to the design of RFID tag antennas in some special environment, such as the identification of liquid-filled bottles. It is crucial to further explore cost-effective RFID tag antenna solutions for liquid-filled bottles [4]. Furthermore, the resonant frequency of the RFID tag antenna may shift significantly in the complicated environment, for example, the presence of other nearby objects, the difference of liquid contents in the bottle or the variation of the bottle shapes. To compensate the frequency shifting, a broader bandwidth is preferred for the RFID tag antenna design. In particular, it is challenging to design a high-performance UHF RFID tag antenna suitable for placing on a liquid-filled bottle or container, due to the high conductivity, high relative permittivity (about 80) and the variety of liquids. Although many structures have been proposed [3–5], they are still big, inefficient, or not easy to use.

In this paper we design through a series of structure evolutions a UHF RFID tag antenna that can work well on the surface of a liquid-filled bottle. The main body of the tag antenna consists of a folded dipole and a loop impedance matching structure. A simple tag antenna using a single-loop impedance

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matching structure is designed first. Then we fold the dipole to reduce the size of the tag antenna and improve the gain. Finally, the single-loop structure is replaced by a three-loop structure to introduce more resonances, which can optimize the impedance matching and broaden the impedance bandwidth. Full-wave simulation is carried out for the performance analysis and parameter optimization using the commercial software CST [6]. In order to measure the impedance of the tag antenna, two different impedance measurement methods are discussed.

2. TAG ANTENNA DESIGN

2.1. A Simple Design and Experimental Verification

Figure 1 shows the simulation model of a simple UHF RFID tag antenna placed on the surface of a water bottle and the corresponding material layers. The simple tag antenna consists of two parts printed on an 80 mm × 24 mm polyimide antenna substrate: the folded dipole and the single-loop matching structure evolved from the T-match structure. The dimensions of the single-loop matching structure are key parameters for impedance matching, which include length a, width b and line width w. The folded dipole arms consist of a pair of 'umbrella-type' folded dipole with lengths L_0, L_1 and g, and their dimensions have a significant effect on the gain performance. There is a gap in the center of the tag antenna for the integration of the IC. In the simulation model, the material layers are the antenna conductor, antenna substrate, plastic bottle, and water from top to bottom. The values for these parameters are shown in Table 1.

In order to simulate the influence of the liquid to the antenna performance and the impedances of the tag antenna and IC, we use a co-design approach, which includes water, plastic bottle, substrate of the antenna and tag antenna conductor in the same electromagnetic environment. In this design, the conductivity and permittivity for water are chosen according to [8] as $\sigma_{\text{water}} = 0.267\,\text{S/m}$ and $\varepsilon_{r,\text{water}} = 79.2$, while the permittivity values for the bottle and substrate are $\varepsilon_{r,\text{bottle}} = 2.19$ and $\varepsilon_{r,\text{substrate}} = 3.18$, respectively [3]. IC 'Alien Higgs-3' [7] is integrated at the center of the tag antenna,

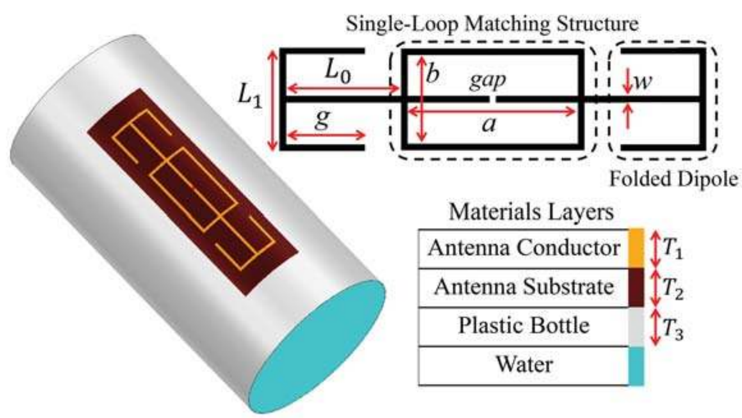


Figure 1. The simulation model for the simple UHF RFID tag antenna placed on a water bottle: the structure of the tag antenna and the materials layers.

Table 1. Numerical values of the parameters (mm) for the simple design.

gap	a	b	w	g	L_0	L_1
1	26	13.7	1	12	17.5	8.5
T_1	T_2	T_3				
0.018	0.2	0.56				

and the IC is defined by the lumped port in the CST.

It is well known that the realized radiation efficiency of the tag antenna is severely limited by the presence of water, and the power transmission coefficient (τ) is given by:

$$\tau = \frac{4\mathrm{Re}(Z_{\mathrm{tag}}) * \mathrm{Re}(Z_{\mathrm{IC}})}{|Z_{\mathrm{tag}} + Z_{\mathrm{IC}}|^2} \tag{1}$$

where Z_{tag} and Z_{IC} are the input impedances of the tag antenna and the IC, respectively. $Z_{\mathrm{tag}} = R_{\mathrm{tag}} + jX_{\mathrm{tag}}$ represents the complex impedance of the tag antenna, and $Z_{\mathrm{IC}} = R_{\mathrm{IC}} + jX_{\mathrm{IC}}$ represents the complex impedance of the IC. The power transmission coefficient indicates what percentage of available power from the antenna is delivered to the IC [9], and maximum power transmission coefficient at the antenna port can be obtained through conjugate matching for the impedance values of the antenna and IC. The impedance of the IC is not given in the handbook directly, but we can calculate it according to the equivalent circuit. The calculated impedance of the IC is $(24.5 - j190)\,\Omega$ at 915 MHz, the real and imaginary parts of which correspond to the resistance and capacitance. The capacitance is about eight times the value of the resistance, indicating that the matching of the imaginary part of the impedance has a more pronounced effect on the impedance bandwidth of the tag antenna. Therefore, in order to obtain a wider impedance bandwidth in the frequency band of interest, we hope that the input impedance should keep stable, particularly the imaginary part.

In general, the impedance bandwidth of the tag antenna is judged by the power reflection coefficient ($|\Gamma_m|^2$) determined by the input impedances of the tag antenna and the IC, i.e.:

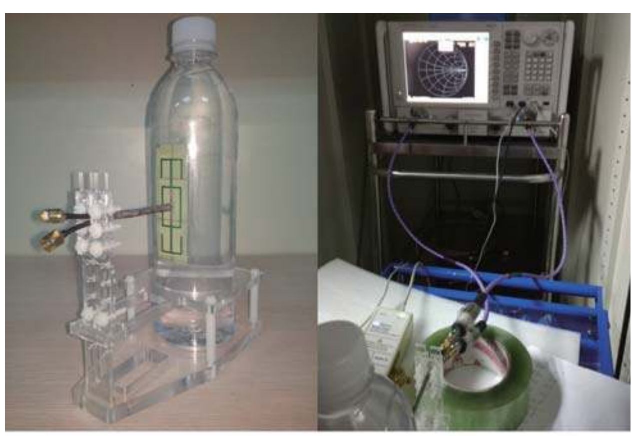
$$|\Gamma_m|^2 = \left|\frac{Z_{\mathrm{IC}} - Z^*_{\mathrm{tag}}}{Z_{\mathrm{IC}} + Z_{\mathrm{tag}}}\right|^2 = 1 - \tau \tag{2}$$

where Z^*_{tag} is the complex-conjugate of the input impedance of the tag antenna. To measure the input impedance of the tag antenna, the balanced design can be treated as an equivalent two-port network [10]. The impedance is characterized by measuring the network S-parameter in this paper. For the symmetrical balanced antenna, $S_{11} = S_{22}$, and $S_{12} = S_{21}$. Converting the Z-parameter to S-parameter and expressing the impedance of the antenna as $Z_d = Z_0 \cdot \tilde{Z}_d$, we have

$$Z_d = \frac{2Z_0\left(1 - S_{11}^2 + S_{21}^2 - 2S_{12}\right)}{(1 - S_{11})^2 - S_{21}^2} \tag{3}$$

where Z_0 is the characteristic impedance of the connected transmission line ($50\,\Omega$ for most of the measurement instruments).

The configuration of the measurement system is shown in Fig. 2(a). An acrylic clamp is designed, which can avoid the deviation of the impedance measurement caused by the movement of the water



(a) (b)

Figure 2. (a) The configuration for the measurement. (b) The impedance measurement using an Agilent N5247A network analyzer.

bottle and the two coaxial cables (with 2.2 mm-diameter outer conductors soldered together and fixed to the clamp). Two different SMA connectors (SMA-J & SMA-K) are used to distinguish the two ports of the tag antenna during the test. One end of the two-port network is cable-connected to the VNA, while the inner conductors at the other end are extended as a probe to touch the tag antenna to be measured [11].

Figure 3(a) illustrates the simulated and measured impedance of the simple tag antenna. We make the simulated input impedance of the tag antenna conjugate impedance matching with the IC at 915 MHz. The measurement results show that the real part of the tag antenna is equal to 24.5 Ω at 890 MHz. Fig. 3(b) shows the simulated and measured power reflection coefficient $|\Gamma_m|^2$ of the simple design. The simulated −6 dB impedance bandwidth is about 51 MHz (from 891 MHz to 942 MHz), and the measured one is also 51 MHz (but shifted a bit from 886 MHz to 937 MHz). The simulated curves of the gain for the simple design is shown in Fig. 3(c), which is nearly vertically omnidirectional also that it can be less shaded by the water bottle around it (as compared to a horizontally omnidirectional pattern). Since the tag antenna is placed on a water bottle, the folded dipole is deformed along the curved surface of the water bottle. Therefore, the curve of the gain has some 'valley' shape near Theta = 0° and Theta = 180° in xz-plane (Phi = 0°).

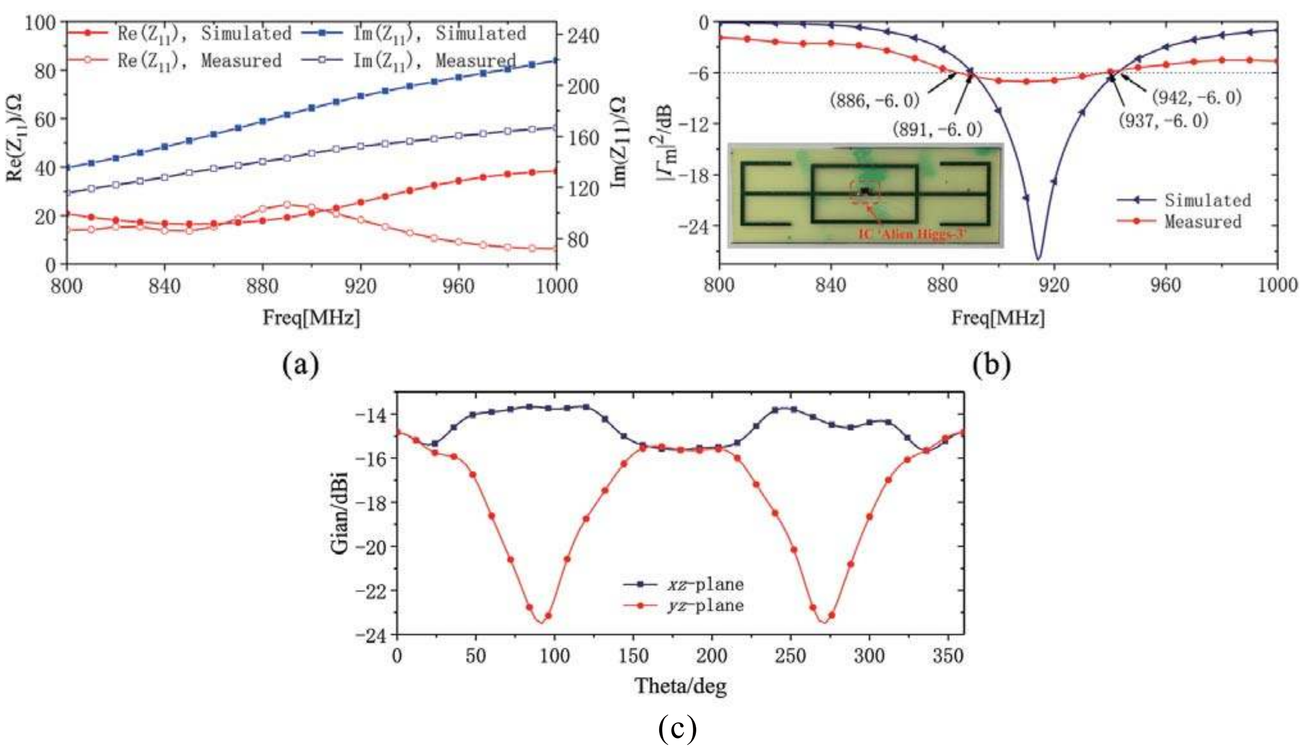


Figure 3. (a) The simulated and measured input impedance of the simple design. (b) The simulated and measured $|\Gamma_m|^2$ of the simple design. (c) The simulated curves of the gain for the simple design.

As a tag antenna, the reading range R_{tag} is important, and can be estimated by

$$R_{\text{tag}} = \frac{\lambda}{4\pi}\sqrt{\frac{\chi_p G_r \text{EIRP}}{P_{ic,0}}} \tag{4}$$

where χ_p is the polarization mismatch factor between the reader and the tag antennas. A good polarization alignment ($\chi_p = 1$) is assumed in this paper. G_r is the realized gain of the tag antenna given by $G_r = \tau G_{\text{tag}}$. EIRP (effective isotropic radiated power) is the limitation of the transmitted power of the reader as listed in Table 2 [3]. The reading range is then determined by the −20 dBm tag IC wake-up power reported by the manufacturer [7]. The measurement results show the reading range

Table 2. RFID frequency and the corresponding EIRP limitations in different regions.

Region	EU	US	Japan
f [MHz]	865.6–867.6	902–928	952–956.4
EIRP [W]	3.28	4	4

of the simple design can reach 4.2 m on a water bottle when working at 915 MHz (for US region). Note that our tag antenna also works in air, and can reach 8 m in the absence of the water bottle. Due to insufficient impedance bandwidth of the single-loop matching structure, the reading ranges of our tag antenna on a water bottle at 866.6 MHz (for EU region) and 954.2 MHz (for Japan region) are only 0.8 m and 2.0 m, respectively. Below we will improve the gain first with an optimized folded dipole.

2.2. Gain Improvement with an Optimized Folded Dipole

Since the current distributions in the parallel dipole arms (the dipole arms with lengths g and L_0 in the 'umbrella-type' folded dipole) in the left and right parts of the simple design are in opposite directions, their contributions to the far field radiation will cancel out each other. Therefore, we should change the structure of the folded dipole to improve the gain of the tag antenna. Fig. 4 shows the improved tag antenna design with an optimized folded dipole, which is printed on a 56 mm × 24 mm antenna substrate. In order to keep the same electric dipole length as the simple design for fair comparison, we define L_{arm} as the total length from the outermost loop to the end of the folded dipole, which is estimated to be 22 mm through some simulation at 915 MHz. The optimized parameters d, d_0 and L

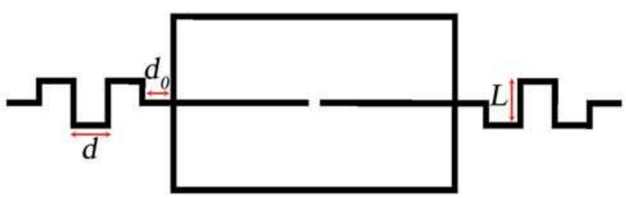


Figure 4. The structure of an improved design with an optimized folded dipole.

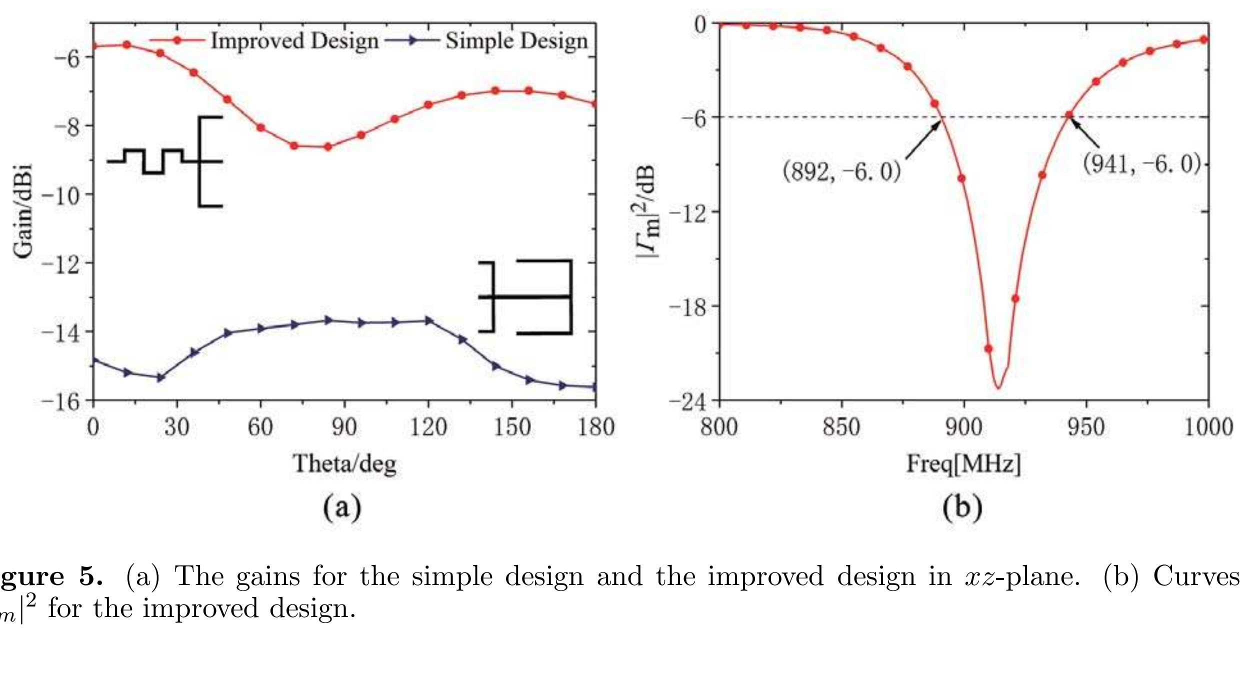


Figure 5. (a) The gains for the simple design and the improved design in xz-plane. (b) Curves of $|\Gamma_m|^2$ for the improved design.

(see Fig. 4) are 2.5 mm, 1 mm and 3.5 mm, respectively.

Figure 5(a) illustrates the curves of the gain in xz-plane for the simple design and the improved design. The gain of the improved design with the optimized folded dipole has been significantly improved, and the maximum gain -5.7 dB is obtained at Theta $= 0°$ in xz-plane. The structure of the optimized dipole is smaller than the 'umbrella-type' folded dipole, and thus the deformation of the tag antenna along the circumference of the water bottle is much smaller. Consequently, the gain of the tag antenna not only has been significantly improved, but also becomes smoother. Curve of $|\Gamma_m|^2$ the improved design is shown in Fig. 5(b). Since the impedance matching structure has not been changed, the -6 dB impedance bandwidth is still about 50 MHz at 915 MHz. Below we will improve the bandwidth so that the UHF tag antenna works in all the three major regions.

2.3. Bandwidth Improvement with Multi-Loop Matching Structure and Experimental Verification

The gain of the tag antenna has been improved after optimizing the folded dipole, but the impedance bandwidth is still narrow, which cannot meet the requirement of wideband matching in all the three major regions (see Table 2). By analyzing the simulation results for the antenna impedance, we found that the key to improve the impedance bandwidth was to make the input impedance of the tag antenna as stable as possible as the frequency shifts within the frequency band of interest. Therefore, we propose a multi-loop structure to improve the impedance bandwidth of the tag antenna. Our simulation results show that the impedance bandwidth of the tag antenna can be widened significantly when the total number of loops is three or more. Furthermore, in order to ensure that the dimension of the antenna is not too large to integrate on the bottle surface, here we choose a three-loop matching structure. The tag antenna consists of the improved folded dipole and a multi-loop matching structure, as shown in Fig. 6, which is printed on a $44\,\text{mm}\,(L_p) \times 20\,\text{mm}\,(W_p)$ antenna substrate. The loop dimensions u and v, increase and the loop width w_m decreases from the inner to outer loops by geometric ratios k_u, k_v and k_{w_m}. The related parameter values are shown in Table 3.

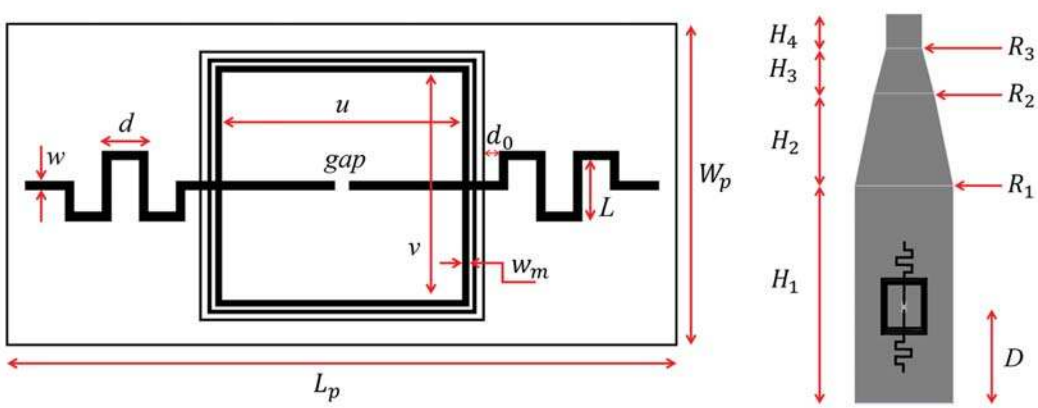


Figure 6. The UHF tag antenna with a multi-loop matching structure, and its placing on a water bottle.

Table 3. Numerical values of the parameters (mm) for the simple design.

gap	u	v	w_m	w	d_0	d	l	k_u
1	17.2	16.2	0.4	0.6	1	2.5	3.5	1.06
k_v	k_{w_m}	L_{arm}	T_1	T_2	T_3	H_1	H_2	H_3
1.06	1.75	24.1	0.125	0.018	0.56	123	56	26
H_4	R_1	R_2	R_3	D	L_p	W_p		
26	32	22.3	13.3	62	44	20		

Figure 7(a) shows the curves of $|\Gamma_m|^2$ with different impedance matching structures. It demonstrates that the single-loop matching structure gives a narrow bandwidth, while the three-loop matching structure gives a much broader bandwidth for the tag antenna. Specifically, the -6 dB impedance bandwidth for the tag antenna with this three-loop matching structure coves a wide band from 863 MHz to 963 MHz, which covers nearly all the UHF RFID bands around the world. Fig. 7(b) illustrates the gain pattern in the xz-plane and xy-plane at 915 MHz, which is also nearly omnidirectional vertically. In particular, the maximum gain of this design can reach -5.54 dBi in the xz-plane after optimizing the dimensions of the matching structure and the length of the folded dipole.

Here we also use an alternative impedance measurement method using a baffle board for the RFID tag antenna of balanced structure, which is simple in operation and low in cost. Compared with the previous method of network parameter characterization, it can be used as a convenient and effective testing method although the accuracy is a bit lower. The measurement system of the baffle board method is shown in Fig. 8. Half of the structure of the balanced RFID tag antenna is intercepted, and this half of the structure is placed vertically on the copper plate. The SMA connector passes vertically from the backside of the copper plate. The central pin of the SMA connector is connected to the feeding point of the RFID tag antenna, and the ground pin is soldered to the copper plate. The copper plate is then placed in a steel plate that retains the hole location of the SMA connector. A coaxial cable is used to connect the antenna to the VNA from the backside of the steel plate. The metal reflector provides

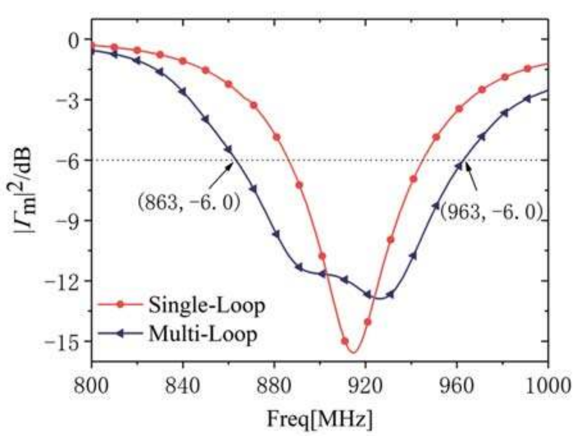


Figure 7. Curves of $|\Gamma_m|^2$ for different matching structures.

Figure 8. Impedance measurement by a baffle board method.

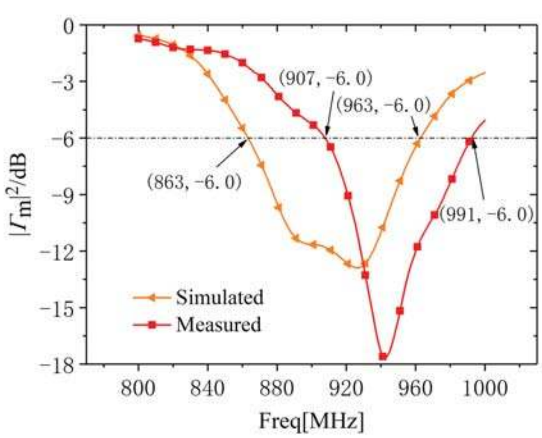


Figure 9. The simulated and measured bandwidths of the antenna with a multi-loop matching structure.

a special mirror so that the current distribution remains the same as that for the whole balanced tag antenna. The actual balanced RFID tag antenna has an input impedance that is twice the impedance of the measured half-structure antenna. The accuracy of this method depends on the size of the reflective metal plate, and it is only applicable for a balanced antenna with a symmetrical structure [12, 13]. Fig. 9 illustrates the results of simulated and measured bandwidths of our tag antenna with three-loop matching structure. The central frequency of the measured results is offset from 913 MHz (designed value) to 949 MHz, which may be caused by the change of the testing environment, the approximate method of measurement and the measurement errors. However, the measured −6 dB bandwidth is 84 MHz, which verifies that the impedance bandwidth has been significantly improved by the multi-loop matching structure.

2.4. Performances of Tag Antenna with a Multi-Loop Matching Structure

The tag antenna with a three-loop matching structure gives a wider impedance bandwidth and a higher gain, as verified by both the simulation and measurement. Furthermore, in order to simulate the characteristic of the proposed antenna in practical environment, we simulated and compared the performance of the tag antenna mounted on different bottles. In our previous design, the tag antenna is placed on a plastic bottle of 0.56 mm thick, with a dielectric constant of 2.19, and the gain can reach −5.54 dBi in the xz-plane as shown in Fig. 10(a). When the bottle material is replaced with a glass with a thickness of 2 mm and a dielectric constant of 5.5, the maximum gain of the tag antenna decreases to −11.1 dBi in the xz-plane (see Fig. 10(c)). Comparing the performances of the tag antenna mounted on an empty plastic bottle and an empty glass bottle, one sees that the values of the maximum gain almost remain the same (about 2.44 dBi; see Figs. 10(b) and (d)). It is concluded that the tag antenna with a three-loop matching structure performs optimally in both the waterless case and the case when it is on the surface of liquid-filled plastic bottle. Although the gain of the three-loop matching structure antenna may decrease as the bottle material changes (with water filled inside), it can still reach the level of Reference [5].

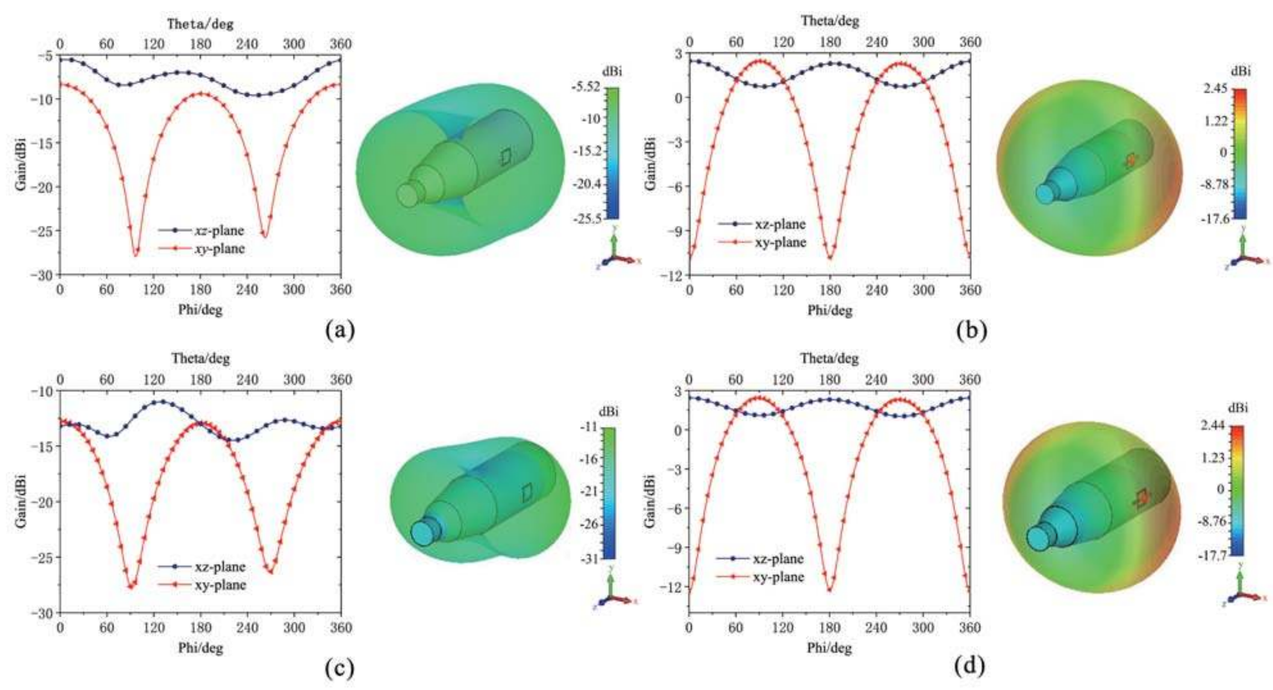


Figure 10. The gain and radiation pattern for the antenna with a three-loop matching structure at 915 MHz. (a) on a plastic bottle filled with water; (b) on an empty plastic bottle; (c) on a glass bottle filled with water; (d) on an empty glass bottle.

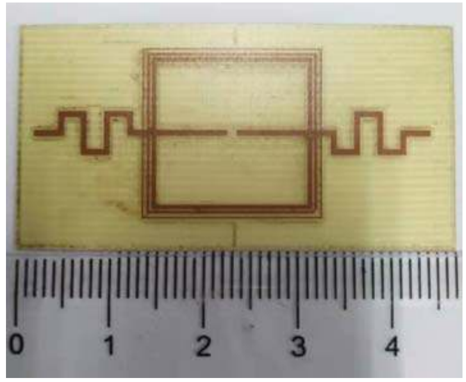


Figure 11. Photograph of the fabricated tag antenna with a three-loop matching structure.

A photograph of the fabricated tag antenna with a ruler is shown in Fig. 11. To compare with some UHF RFID tag antennas in the literature, a performance summary of the tag antennas is given in Table 4, from which one sees that the reading range of the proposed tag antenna is obviously better than [3] and [5] at the central frequency of 915 MHz and higher frequencies, though slightly smaller than [5] at 866.6 MHz. In addition, the size of the proposed structure is less than a quarter of [5] and about a half of [3].

Table 4. Comparative summary of the antenna performance.

Type	Size	f [MHz]	τ	G_{tag} [dBi]	R_{tag} [m]
[3]	86 mm × 23 mm	915	-	-	0.54
[5]	88 mm × 58 mm	866.6	0.98	−9.7	3.3
		915	0.34	−10.8	2.7
		954.2	0.17	−10.3	2.0
Proposed Tag	44 mm × 20 mm	866.6	0.71	−9.2	1.45
		915	0.95	−5.54	5.6
		954.2	0.49	−7.2	4.8

3. CONCLUSION

In this paper we have shown how to design a high-performance UHF RFID tag antenna placed on a liquid-filled bottle. First a simple design has been proposed for a UHF RFID tag antenna suitable to place on a water bottle. The tag antenna consists a folded dipole and a loop matching structure, and a co-design approach has been used to include the water and bottle surface as parts of the tag antenna to eliminate the significant influence of the environment. The measured reading range for the tag antenna of this simple design is about 8 m in the absence of the water bottle and can still reach 4.2 m when it is placed on a water bottle at 915 MHz. We have then optimized the folded dipole on the water bottle to improve the gain significantly, and a maximum gain of −5.54 dBi has been achieved at 915 MHz. The impedance bandwidth for the tag antenna on the water bottle has also been significantly improved by using three loops in the impedance matching structure. The −6 dB bandwidth of over 100 MHz (simulation) or 84 MHz (experiment) has been achieved, as well as a reading range of 5.6 m when the tag antenna is placed on a water bottle at 915 MHz.

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