An Internal Coupled-Feed UHF RFID Tag Antenna with CP and Metal-Mountable Advantage

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Abstract. An internal coupled-feed microstrip RFID tag antenna for UHF band is presented in this article. To achieve a compact size, the orthogonal cross-slot is etched on the radiation patch, reducing antenna size and providing feeding space for L-shaped feedline. In order to meet the metal-mountable advantage and the low-profile size requirement, the ends of L-shaped feedline are connected with ground through metal-via. By optimizing the size of L-shaped feedline, the expected input impedance of the proposed tag antenna can be obtained easily. Moreover, the target band of circular polarization (CP) can be covered by optimizing the length of slits, which is embedded in the four corners of the radiation patch. The measured 3-dB Power Reflection Coefficient (PRC) bandwidth of the proposed tag antenna is 98 MHz (from 840 to 938 MHz), and its 3-dB axial-ratio (AR) bandwidth is 7 MHz (from 920 to 927 MHz). Further test results demonstrate that the tag antenna can provide better gain and reading range when mounted on a metal plate.

1. Introduction

In recent years, the applications of radio frequency identification (RFID) in the ultra-high frequency (UHF) band (860-960 MHz) are expanding exponentially, due to the advantages such as long reading distance, high data transfer rate, and small tag size [1]. Nowadays, tag antenna with circular polarization (CP) and anti-metal advantage have drawn much attention. This is because the commercial RFID systems require CP reader antenna to obtain orientation diversity. However, the majority of available RFID tags in the UHF band commonly use linear polarization (LP) antenna [2]-[4]. Thus, the polarization mismatch between the reader antenna and tag causes an unwanted decrease in the recognition distance. Moreover, the reading range of the RFID system will significantly drop when the non-metal-mountable tags [4] are mounted on a metal object.

Recently, many researchers have carried out research work on tag antennas [1]-[6] to improve the recognition performance of UHF RFID systems, such as designing the linear polarization (LP) tag antenna [2]-[4] with the ability of mounting on metallic surfaces. Although the recent study in [5] exhibits a CP tag antenna with Crossed-Dipole structure. However, it misses the metal-mountable advantage. The metal mountable CP tag antennas with outstanding impedance conjugate matching
skills have been proposed in [1], [6]. However, the increasing antenna size requires additional areas for feeding structures.

In this article, an internal coupled feed tag antenna with CP and metal mountable advantage is proposed. An orthogonal cross-slot is etched on the antenna to reduce the antenna size. Instead of providing extra space for the feeding unit, a terminal-grounded L-shaped feedline is embedded in the orthogonal cross-slot, to obtain a more compact structure. Besides the compact structure, the impedance conjugate matching with tag chip can be easily achieved by optimizing the size of L-shaped feedline. By slightly varying the length of the unequal slit in four corners of the antenna, CP radiation in 920-927 MHz band can be obtained easily. Further test results demonstrate that the tag antenna can provide better gain and reading range when mounted on metal plates of different sizes.

2. Antenna Configuration and Impedance Matching Technique

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{antenna_configuration.png}
\caption{Geometry of the proposed CP RFID tag antenna (unit: mm)}
\end{figure}

\begin{table}[h]
\centering
\caption{Optimized design parameters of the proposed tag antenna (unit: mm)}
\begin{tabular}{|c|c|c|c|c|}
\hline
Lg & Lp & S_L & W & L_1 \\
\hline
65 & 50 & 42 & 3.1 & 27.1 \\
\hline
L_2 & W_f & S_{l1} & S_{l2} & W_s \\
\hline
10.9 & 1.2 & 8.2 & 3.8 & 2.2 \\
\hline
\end{tabular}
\end{table}

The proposed CP RFID tag antenna as shown in Figure 1 is fabricated on a cheap FR4 substrate, with thickness 1.6mm and relative permittivity 4.4 (loss tangent 0.02). The opposite side of the ground plane (65 × 65 mm\(^2\)) is a square radiation patch (50 × 50 mm\(^2\)) centrally loaded by an orthogonal cross-slot of lengths (S_L), width (W). The orthogonal cross-slot aims to excite two orthogonal field components for CP radiation. The rectangular slits with a length of S_{l1} and S_{l2} are put on the diagonal of the square radiation patch, and the width of slits are all W_s. An L-shaped feedline, with a width of W_f is embedded in the orthogonal cross-slot to form the internal coupled feed structure. The L-
shaped feedline contains the two parts of feedline 1 and feedline 2, which have unequal lengths, \(L_1\) and \(L_2\), to link the tag chip and short contact to the ground plane.

The L-shaped feedline can also match the impedance of the Alien Higgs 3 tag chip with an input impedance of 13.5-j110 Ω at 915 MHz, which was also used in [6], and has a threshold power sensitivity of approximately -14dBm over the RFID UHF operating band of 902-928 MHz. In order to achieve the greatest transmission energy from the chip to the antenna, the complex impedance of the antenna should be set to 13.5+j110 Ω. To get the reactance of 111jΩ, the initial dimensions of the L-shaped feedline should be calculated by the short-circuited transmission line theory, the detailed formula [7] is as follows:

\[
L_1 + L_2 = \frac{\lambda_g}{2\pi} \arctan(110/Z_0)
\]

Where \(\lambda_g\) is the guided wavelength at 915 MHz, and \(Z_0\) means the characteristic impedance of the L-shaped feedline that can be determined by the width \(W_f\) after the material and thickness of the dielectric substrate is determined. Then, the calculated value of \((L_1 + L_2)\) which equals to 27.6 mm is obtained. Considering the effects of electromagnetic coupling between the feed and radiating elements, the actual length of the antenna L-shaped feedline is 38 mm to guarantee the antenna of 13.5+j111Ω at 915MHz. Therefore, we have realized the antenna and chip conjugate impedance matching with each other. The optimized design parameters of the proposed tag antenna are tabulated in Table 1.

3. Results and Discussions

The design and simulation of the tag antenna were implemented by using the ANSYS HFSS, in which the impedance matching and circular polarization performance of the proposed tag antenna can be studied more systematically. Here, the input impedance of the proposed tag antenna was measured by applying the method in [8].

3.1. Input impedance

In Figure 2, both the measured and simulated input impedance of the proposed tag antenna are presented, the measured input reactance is between 106 to 126 Ω, while its corresponding input resistance range from 2.8 to 14.3 Ω. To further demonstrate that the input reactance is mainly related by the size of the L-shaped feedline, the input reactance simulation values when only the feedline (getting rid of the radiation patch) included in Figure 2. The figure shows that the three results (measured, simulated, and only feedline simulated) of tag antenna inductive reactance at 915 MHz are close. The additional reactance was produced by radiation patch, and the inductive reactance value of the tag antenna was slightly smaller than its value without radiation patch. In Figure 3, the associated 3-dB power reflection coefficient (PRC) [9] measured bandwidth of the proposed tag antenna is 98 MHz (from 840 to 938 MHz), which completely covers the critical band (902-928 MHz). The PRC formula is as follows:

\[
PRC(\text{dB}) = 20 \log_{10} \left( \frac{Z_L - Z_t^*}{Z_L + Z_t^*} \right)
\]
3.2. Realization of CP bandwidth by adjusting the slit length
In this section, the effects on CP bandwidth of the proposed tag antenna by tuning the lengths of the slit were studied. There, case 1 and case 2 with slit lengths of \( S_{l1} = 8.2 \text{ mm} \), \( S_{l1} = 3.8 \text{ mm} \) and \( S_{l2} = 10.2 \text{ mm} \), \( S_{l2} = 1.8 \text{ mm} \) respectively, were researched through simulation, in which the corresponding amplitude ratio \( \left( \frac{|E_x|}{|E_y|} \right) \) and phase difference \( (\phi_x - \phi_y) \) of the two orthogonal radiation fields \( E_x \) and \( E_y \) in the boresight direction are shown in Figure 4. The phase difference and amplitude ratio of case 1 at 923 MHz are 92 degrees and 1.075 respectively, the values of case 2 at 913 MHz are 92.7 degrees and 0.998 respectively, which was satisfied the circular polarization requirements of \( E_x \) and \( E_y \) in the boresight direction with equal amplitude and 90
degrees phase difference. Figure 5 shows the AR bandwidth of case 1 and case 2, which are 909-916 MHz and 920-927 MHz respectively, and the outstanding simulation PRC bandwidth of case 1 and case 2 are illustrated in Figure 6. The 3-dB AR bandwidth of case 1 can apply to China, Hong Kong, Taiwan, Singapore and Australia, while the 3-dB AR bandwidth of case 2 exactly covers the UHF RFID band in Korea. Therefore, the simulation results show that the CP bandwidth can be realized by adjusting the slit length.

Figure 4. Simulated the amplitude ratio and phase difference of the radiation fields (\( E_x \) and \( E_y \)) in the boresight direction. Case 1: \( S_{11} = 8.2 \, \text{mm}, \ S_{12} = 3.8 \, \text{mm} \); Case 2: \( S_{11} = 10.2 \, \text{mm}, \ S_{12} = 1.8 \, \text{mm} \).

Figure 5. Simulated axial ratio of the antenna studied in Figure 4.
Figure 6. Simulated PRC of the antenna for Case 1 and Case 2.

Figure 7. Simulated surface current distributions of the antenna at 923 MHz.

Figure 8. Simulated AR radiation patterns at 923 MHz for the antenna.
In order to further explain CP characteristics of the proposed tag antenna, the surface current distributions of radiation patch at 923 MHz are plotted in Figure 7, showing the direction of the surface current distribution at different time phases (\(\omega t\)) from 0° to 270° with 90 degrees steps. In this figure, it is clearly observed that the direction of the radiation patch surface current presents a counter-clockwise rotation as \(\omega t\) increases, which leads to a right-handed circularly polarized (RHCP) radiation. Moreover, the simulated AR radiation patterns at 923 MHz are shown in Figure 8. The 3-dB AR beamwidths are 115° and 116° respectively, in x-z and y-z plane. Obviously, a wide beamwidth and RHCP radiation behavior are obtained.

3.3. The metal-mountable advantage
Because the input impedance of the tag antenna cannot match the 50\(\Omega\) characteristic impedance of the coaxial test line, so, the microwave anechoic chamber is unable to measure the CP performance and far-field radiation patterns of the tag antenna. Therefore, Figure 9 only presents the simulated radiation patterns at 923 MHz for the proposed tag antenna placed in free space and on a 300 \(\times\) 300 mm\(^2\) metal plate. It is clearly that the values of \(E_\theta\) and \(E_\phi\) in the boresight direction are approximately equal when the tag antenna is mounted both in free space and on a metal plate. It proves that the proposed tag antenna has excellent CP radiation characteristic and metal-mountable advantage. Moreover, reduced back radiation is also observed when the tag antenna is mounted on a metal plate.

![Figure 9](image)

**Figure 9.** Simulated radiation patterns at 923 MHz for the proposed tag antenna. (a) In free space. (b) On a 300 \(\times\) 300 mm\(^2\) metal plate.
Figure 10. Simulated antenna gains for the proposed tag antenna placed in free space and on metal plates of different sizes.

Figure 10 shows the simulated gains when the tag antenna was mounted in free space and on metal plates of different sizes. In this figure, it is obvious that the tag antenna has excellent anti-metal ability, and the gain will maintain around -7 dBic as long as the metal plate size is larger than $100 \times 100 \text{mm}^2$.

3.4. The measurements of recognition distance

An RFID reader module (AS3992) with 20 dBm output power at the 902-928 MHz band and an LP reader antenna (HBDRFD-D10V30A) with 10 dBic gain are used to measure the recognition distance of the proposed tag antenna (adopting Alien Higgs-3 chip, with -14 dBm threshold power). As shown in Figure 11, the maximum recognition distance was measured by rotating the proposed tag along with the $\varphi$ direction, when the tag was mounted in the free space or on metal plates of different sizes. For the free space condition, the recognition distances vary between 0.58 and 0.62 m at all $\varphi$ degrees. More importantly, slightly increased recognition distances between 1.03 and 1.15m are obtained when the tag was mounted on a $300 \times 300 \text{mm}^2$ metal plate. Therefore, this result further proved that the proposed antenna is intensely CP and has an obvious metal-mountable advantage.

Lastly, the measured reading ranges obtained by respectively using the LP and CP reader antenna are shown in Table 2. It is obvious that the measured values by using the CP reader antenna are approximately 0.1m longer than those of LP reader antenna due to the polarization matching, even though the gain of CP reader antenna is 2dB lower than the LP reader antenna. Here, we use the Friis formula [10] to calculate the theoretical reading range. By comparing the calculated result with the measured result, the two results are close to each other. The measured result is lower slightly because the Friis formula ignores the interferences of the non-vacuum environment.
Figure 11. Measured recognition distance for rotating the tags along with the $\phi$ direction by using the LP reader antenna with gain $G_r = 10$ dBic.

Table 2. The maximum reading range results of the proposed tag antenna and [1], [7] at 923 MHz.

| Antennas | Conditions     | Simulated Gain ($G_r$) | Reading Range by 10dBic LP Reader Antenna (m) | Reading Range by 8dBic CP Reader Antenna (m) |
|----------|----------------|-------------------------|---------------------------------------------|---------------------------------------------|
|          |                |                         | Meas | Cal | Meas | Cal |
| Proposed | Free Space     | -11.79 dBic             | 0.62 | 0.69 | 0.71 | 0.78 |
|          | 100 $\times$ 100 mm$^2$ metal plate | -8.93 dBic             | 0.91 | 0.97 | 0.94 | 1.08 |
|          | 300 $\times$ 300 mm$^2$ metal plate | -6.28 dBic             | 1.15 | 1.31 | 1.3  | 1.47 |
| [1]      | Free Space     | -14.4 dBic              | 0.5  |      | 0.62 |      |
|          | 100 $\times$ 100 mm$^2$ metal plate | -9.7 dBic              | 0.93 |      | 1.04 |      |
| [7]      | Free Space     | -13 dBic                | 0.63 |      | 0.71 |      |
|          | 400 $\times$ 400 mm$^2$ metal plate | -7.9 dBic              | 1.15 |      | 1.28 |      |

In order to further illustrate the advantages of the proposed tag antenna, a comparison with CP metal-mountable tag antenna [1], [7] is given in Table 2. Please note that the reader module output power of [1], [7] are both 30 dBm, which is higher than the 20 dBm of AS3992 adopted by this paper. The tag chip’s threshold power in [7] is -17.4 dBm, which is lower than -14 dBm of Alien Higgs-3. Likewise, the gain of the reader antenna used in [1], [7] are also different from that in this paper. Thus, for a fair comparison, the hardware parameters of AS3992, Alien Higgs-3 and reader antenna are utilized in this work to calculate the prediction reading range of [1], [7]. As can be seen from the comparison, it is obvious that the theoretical reading distances obtained by the proposed tag antenna are longer than those in [1] and [7]. Moreover, when the proposed tag antenna and the tag antenna in [1] are mounted on the $100 \times 100$ mm$^2$ metal plate, the proposed tag antenna achieved a longer reading distance with a higher gain than that in [1]. This is because the proposed tag antenna obtained a better impedance match than that in [1].
4. Conclusion
An internal coupled-feed UHF RFID tag antenna with the CP and metal-mountable advantage has been successfully demonstrated. A compact antenna structure of $65 \times 65 \text{mm}^2$ is obtained by using an internal coupled feed method. The 3-dB AR bandwidth (920-927 MHz) can be implemented by optimizing the slit length efficiently. Later, the simulation and measured results show that the proposed tag antenna is a good candidate for UHF RFID system, especially when the system requires that the tag antenna needs to be mounted on a metal plate.

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