A Modified Split-Ring Resonator Antenna for Radio Frequency Identification Tag

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Abstract: A compact antenna formed by three concentric split rings for ultra-high frequency (UHF) radio frequency identification (RFID) tag is proposed in this paper. The antenna is composed of two parts, an outer short-circuited ring modified from a traditional split-ring resonator (SRR) antenna and an inner SRR load, so the antenna can be regarded as a short-circuited ring loaded with SRR. According to the transmission line theory, to conjugate match with the capacitive input-impedance of a tag chip, the length of the short-circuited ring is $\lambda_g/4$ shorter than that of an open-circuited dipole of a traditional SRR antenna, where λ_g is the wavelengh of the operating frequency. Hence, the size of the proposed antenna is more compact than that of the traditional SRR antenna. Thereafter, the proposed antenna is simulated and optimized by ANSYS high-frequency structure simulator (HFSS). The impedance, efficiency, and mutual coupling of the fabricated antenna are tested in a reverberation chamber (RC). The results show that the size of the presented antenna is 83% smaller than that of the traditional SRR antenna and the proposed antenna can cover the whole UHF RFID operating frequency band worldwide (840—960 MHz). The measured read range of the tag exhibits maximum values of 45 cm in free space and 37 cm under dense tag environment.

Key words: radio frequency identification (RFID); compact antenna; split-ring resonator (SRR); reverberation chamber (RC); dense tag environment

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0 Introduction

Radio frequency identification (RFID) is a denoting technology that uses electromagnetic waves to uniquely identify tagged objects. An RFID tag generally contains an integrated circuit chip for storing the information about the tagged item and an antenna for receiving and transmitting radio signals. Passive RFID tags can collect electrical energy from a reader to activate the chip and response a modulated wave back to the reader. Due to the small dimension and long read range, passive ultra-high frequency (UHF) RFID tags have become the focus of intense research.

One of the most challenging aspects of RFID tag design is the reduction in antenna size. In practical applications, the dimensions of tag antenna are commonly required to be much smaller than the wavelength for the frequency of operation. Several traditional methods have been reported to reduce the antenna size, such as meandering technique and capacitive tip-loading structure[1-2]. With the flexibility and new properties provided by metamaterials, new types of miniaturized antennas have been conceived[3-4]. Among these, the split-ring resonator (SRR) structure gives an effective technique for the electrically small RFID tag design[5-8]. Zamora et al.[7] presented a compact planar passive UHF RFID tag ($0.23\lambda_0 \times 0.23\lambda_0$) based on an SRR antenna. Zuffanelli et al.[8] proposed an edge coupled SRR tag antenna with size of $\lambda_0/11 \times \lambda_0/11$. Apart from the miniaturization, the mutual coupling

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among tags under dense tag environment needs to be investigated. The reading performance of the RFID system may be degraded when RFID tags are closely stacked together[9-10]. Hence, it is urgently required to develop a compact and reliably tag antenna in short-range reading application.

In this paper, a compact antenna formed by three concentric split rings for UHF RFID tag is presented. The antenna can be regarded as a short-circuited ring loaded with SRR. According to the transmission line theory and the equivalent circuit model, the principles of the traditional SRR antenna and the presented antenna are researched. Then, the presented tag antenna is simulated and optimized by high-frequency structure simulator (HFSS). By analogy with the multipath environment in a metal cabinet, a reverberation chamber (RC) with a similar size is employed to evaluate the radiation performance of the antenna[11-13]. The simulated and measured results show that the antenna has an 83% smaller area than the traditional SRR antenna and can cover all the band of the UHF RFID (840—960 MHz). The measured maximum read range of the presented tag agrees well with the theory values.

1 Antenna Principle

1.1 Miniaturization principle

A traditional SRR tag antenna shown in Fig.1 has been presented and analyzed in detail in Ref.[14]. In the traditional view, an SRR structure is composed of two circular rings with splits at opposite edges. When employing it as a tag antenna, its excitation port is placed across an additional gap in the outer ring. In this circumstance, the antenna can be considered as a curved dipole loaded with a split ring in another view. In the theory of transmission line, the dipole can be regarded as an open-circuited transmission line. To obtain a conjugate match with the capacitive input-impedance of a RFID chip, the minimum length of an inductive open-circuited transmission line is $\lambda_g/4$ longer than that of an inductive short-circuited one, where λ_g is the wavelengh of the operating frequency. As shown in Fig.2, a Smith chart is employed to show the procedure of a conjugate match, in which a solid blue star and a hollow red star represent the chip impedance and its conjugate impedance, respectively. As is well known, clockwise rotation in the Smith chart represents a movement towards the signal source and each revolution on the Smith chart corresponds to moving half wavelength along the transmission line. Obviously, the distance of clockwise rotation from the open-end to the hollow red star is $\lambda_g/4$ longer than that of from the short-end. Hence, if the end of the curved dipole is shorted, a modified antenna with smaller size than that of traditional SRR can be obtained.

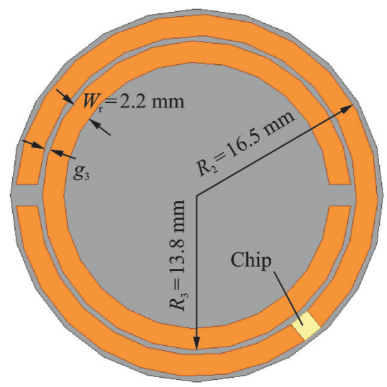


Fig.1 Configuration of the traditional SRR tag

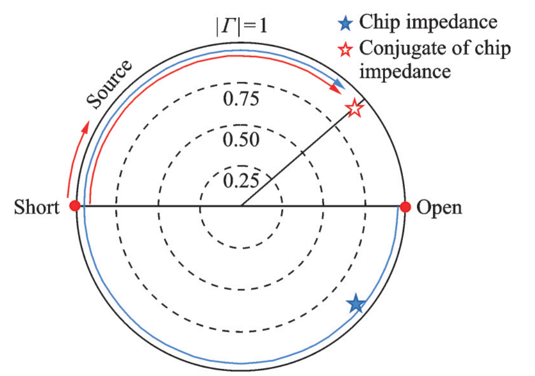


Fig.2 Impedances (normalized to 50 Ω) in a Smith chart

1.2 Equivalent circuit model

The traditional SRR tag is analyzed by an equivalent circuit model[14], as shown in Fig.3. The equivalent resistance and capacitance of the chip port are denoted by R_C and C_C, respectively. The antenna radiation resistance is ignored in the model as its value is small. The equivalent circuit of the SRR structure can be considered as a series of inductances and capacitances[15]. The equivalent inductances consist of the self-inductance L_0 of the ring and mutual inductance L_m between the rings. C_r represents the mutual capacitance between the inner and outer ring, which is divided into two equal parts by splits of two rings. The equivalent capacitances between two splits are denoted as C_s. Both of them are paralleled to the corresponding half of C_r. The circumference of the SRR and the gap width g_3 (Fig.1) between two split rings have great effect on the equivalent inductance and capacitance of the SRR structure.

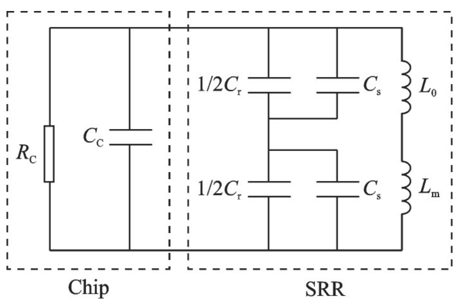


Fig.3 Equivalent circuit model of the traditional SRR tag

To make the antenna compact, the outer ring of the traditional SRR antenna is replaced by a short-circuited ring. At this time, the inner ring will be severely detuned and deviated from the resonant frequency, which acts as a capacitive load to adjust the resonant frequency of the antenna.

2 Antenna Design and Simulation

2.1 Proposed tag antenna based on compact SRR

The proposed tag antenna is printed on a polytetrafluoroethylene (PTFE) substrate with a relative permittivity of 2.55 and a thickness of 0.5 mm, as shown in Fig.4. A Monza 4 chip with an input-impedance of (11-j143) Ω at 920 MHz is used for the proposed tag. To introduce an additional capacitance, a smaller split ring with a radius of R_3 is loaded onto the proposed antenna. An SRR is formed by these two split rings with radii of R_2 and R_3. Therefore, the proposed tag antenna is considered to be formed by the short-circuited ring loaded with the compact SRR, where the short-circuited ring is modified from the traditional SRR antenna.

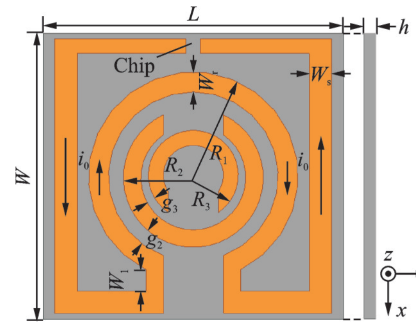


Fig.4 Configuration of the proposed compact passive UHF RFID tag antenna based on SRR structure

An equivalent circuit model of the presented tag antenna is shown in Fig.5. The equivalent inductances of the proposed antenna consist of the self-inductance L_0' of each split ring and the mutual inductance L_m' between split rings. C_L and C_{Lr} represent the self-capacitance of the short-circuited ring and the mutual capacitance between the short-circuited ring and SRR, respectively. It is observed that two equivalent circuit parameters C_L and C_{Lr} are newly introduced in this circuit. They make a great contribution to the reduction of antenna size.

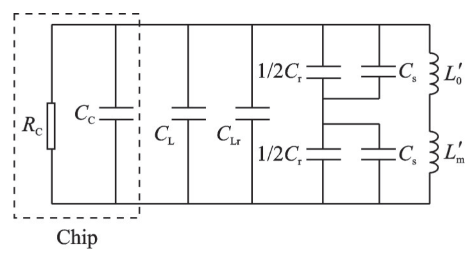
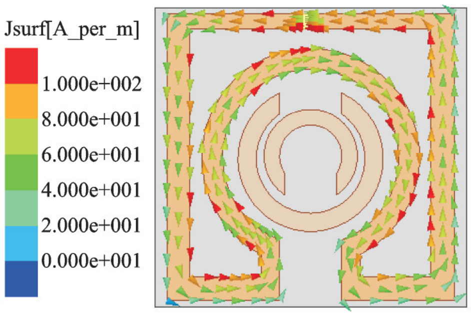
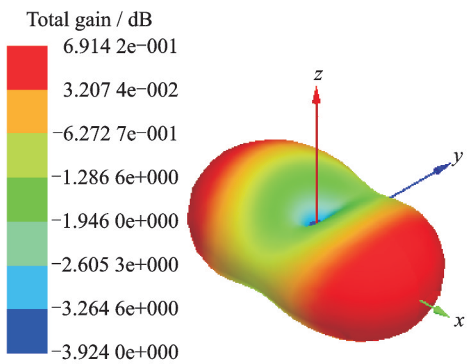


Fig.5 Equivalent circuit model of the proposed compact tag antenna

The simulated vector current density distribution of the proposed tag antenna is depicted in Fig.6(a). It can be seen that the current is mainly concentrated on the outer square loop. The current i_0 on the left and right sides of the outer square loop is opposite to that on the inner ring. Hence, the antenna obtains a bidirectional pattern, as shown in Fig.6(b). Due to the large reduction of antenna size, the split ring loads are too small to resonate at 920 MHz. They are loaded onto the proposed antenna to provide an additional capacitance to adjust the resonant frequency of the antenna slightly.



(a) Simulated electric current density distribution of the proposed tag antenna at 920 MHz



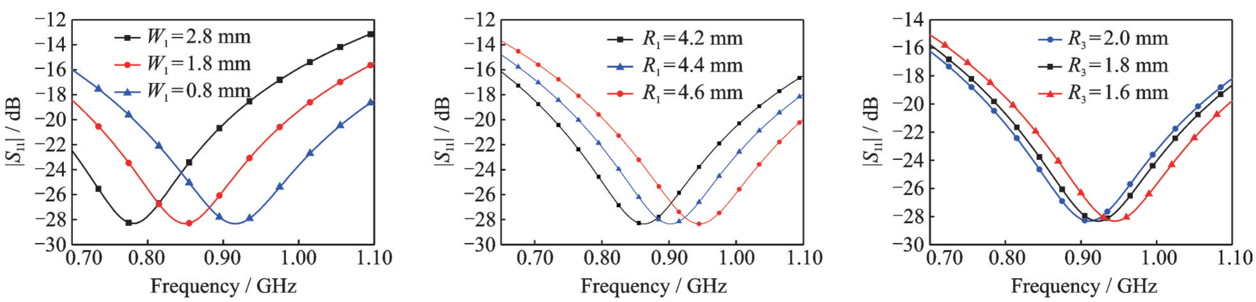
(b) 3D bidirectional gain pattern at 920 MHz

Fig.6 Simulated vector current density distribution and 3D gain pattern of the proposed tag antenna

2.2 Parametric analysis

A parametric study is conducted to examine the effects of the parameters of the short-circuited ring and the SRR at the antenna resonant frequency. In this section, parametric analysis is carried out for W_1, R_1, and R_3. Parameter W varies with W_1 and the other parameters remain unchanged as follows: $L = 12$ mm, $R_2 = 2.8$ mm, $W_r = 0.8$ mm, $W_s = 0.9$ mm, and $h = 0.5$ mm. The antenna is analyzed by HFSS.

The dimension of the outer square loop has a great effect on the resonant frequency of the antenna. An increase of the length of the tag W_1 can result in a lower resonant frequency, as shown in Fig.7(a). Once the dimensions of the outer square loop are fixed, the key parameter affecting the resonant frequency of the antenna is the radius of the inner folded ring. By decreasing R_1 to increase the gap width g_2, the capacitance of the presented antenna can be reduced. This leads to the decrease of the resonant frequency of the antenna, as shown in Fig.7(b). For the loaded compact SRR, the radius of the inner split ring is the primary variables for the shift of the antenna resonant frequency. Keep the value of R_2 unchanged, an increase of R_3 leads to a decrease of g_3, which may increase the capacitance of the SRR structure. Hence, the antenna resonant frequency can be decreased with the increase of R_3, as shown in Fig.7(c).



(a) W_1 (b) R_1 (c) R_3

Fig.7 Simulated reflection coefficients of the tag antenna with different values

The optimized parameters of the tag antenna are listed in Table 1. The final optimized dimension of the presented antenna is about 12 mm×11.5 mm. Compared with that of the traditional SRR antenna, as shown in Fig.1, it can be seen that the size of the presented antenna is reduced by 83%.

Table 1 Tag antenna dimensions mm

L	W	R_1	R_2	R_3	W_r	W_s	W_1	h
12	11.5	4.2	2.8	1.8	0.8	0.9	0.86	0.5

3 Measurement Results and Analysis

3.1 Impedance measurement

Because of the demand of balanced feeding, a test fixture[16-17], as shown in Fig.8, is employed to measure the antenna impedance with an experimental methodology proposed in Ref.[16]. The length of each coaxial line is 100 mm. The balanced antenna and test fixture are considered as two-port networks. The simulated and measured impedance of the presented tag antenna are shown in Fig.9. The measured real and imaginary parts of the impedance agree with the simulated results. But due to the experimental error caused by the fixture, the test results are not exactly the same as the simulation results.

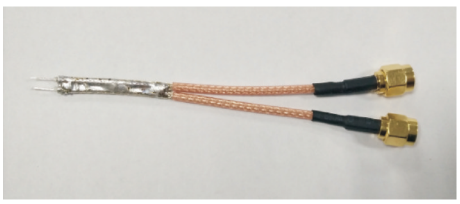


Fig.8 Photograph of the test fixture made up of two coaxial lines of common ground connection

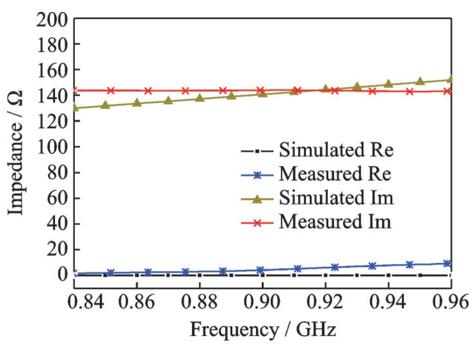


Fig.9 Simulated and measured impedance of the proposed tag antenna

3.2 Measurement of antenna gain and read rang

The antenna gain is measured by using two identical tag antennas, which is a basic method for measuring antenna gain. Assuming the gain of two antennas are the same, the gain can be expressed as

$$G=\frac{1}{2}\left[20\lg\left(\frac{4\pi R}{\lambda}\right)-10\lg\left(\frac{P_{\mathrm{t}}}{P_{\mathrm{r}}}\right)\right] \tag{1}$$

where P_{t} and P_{r} are the transmit power and receive power respectively, and R is the distance between two antennas that needs to subject to the far field condition. In this test, a homemade $\lambda/4$ coaxial balun[17-18] is employed to feed the tag antenna. The balun is the same as that used in Ref.[17]. For the convenience of testing, the gain values are measured every 30° in xy-plane. The gain patterns of the presented tag antenna are demonstrated in Fig.10. The simulated and measured gains in xy-plane are 0.69 dBi and 0.2 dBi, respectively. As expected, a weak bidirectional characteristic of the antenna is obtained.

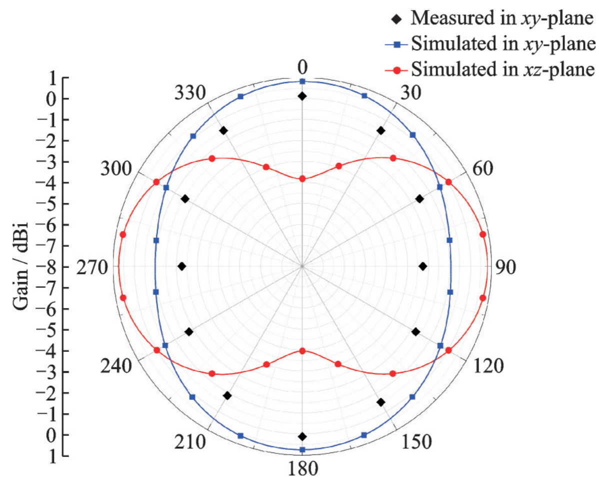


Fig.10 Simulated and measured gain patterns of the proposed antenna in xy-plane and xz-plane at 920 MHz

Thereafter, the read range of the presented tag is measured by a handheld reader in an anechoic chamber, as shown in Fig.11. The tested maximum read range values are agreed well with the theoretical values calculated by

$$R_{\max}=\frac{\lambda}{4\pi}\sqrt{\frac{\mathrm{EIRP}\cdot G_{\mathrm{r}}\cdot\tau}{P_{\mathrm{th}}}} \tag{2}$$

where the equivalent isotropically radiated power (EIRP) of the handheld reader is 4 W, G_{r} the gain of the antenna, P_{th} the minimum threshold power to activate the chip, and τ the power transmission coefficient that can be expressed as $\tau=(1-|\Gamma|^2)$, here Γ is the reflection coefficient of the tag antenna. The sensitivity of Monza 4 chip is −17.4 dBm. The tested results and theoretical values of the maximum read ranges in free space and the dense tag environment are shown in Table 2. Multiple tags are stacked to simulate the dense tag environment with a stacking interval of 5 mm. From the results, the read ranges of the proposed tag in dense tag environment are close to that in free space. This signifies that the mutual coupling has little effect on the tag and the proposed antenna can be employed reliably for RFID tag in dense tag environment.

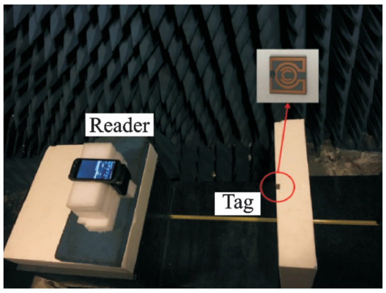


Fig.11 Scenario of read range measurement

Table 2 Maximum read range in free space and dense tag environment cm

Read range	Free space	Dense tag environment
Theoretical value	51	43
Measured value	45	37

3.3 Measurement of efficiency and coupling

By analogy with the multipath environment in a metal cabinet, an RC with a similar size is employed to test the antenna. The dimension of the RC is 1.2 m×0.8 m×1.2 m, as shown in Fig.12. The $\lambda/4$ coaxial balun is used to connect the tag antenna and the coaxial cable. The antenna radiation efficiency is tested by the reference antenna (Ref Ant) method. The antenna under test (AUT) is the proposed tag antenna and the Ref Ant is a wide band Vivaldi antenna with known radiation efficiency of 85%. The measurement method and the scenario can be found in Refs.[13, 17] and the measured results are shown in Fig.13. It is observed that the radiation efficiency of the antenna can over 75% at 920—925 MHz and the matching of the antenna port is fairly good since the total efficiency is closest to the radiation efficiency at 920—925 MHz.

The mutual coupling effect between tag antennas is also investigated in this paper. The coupling

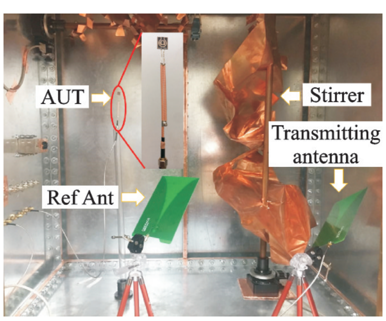


Fig.12 Scenario of the reverberation chamber

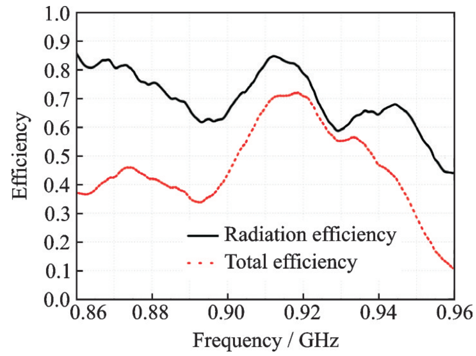


Fig.13 Measured radiation efficiency and total efficiency of the manufactured tag antenna in the RC

values between two identical proposed tags are tested in the anechoic chamber and RC, respectively. The tags are stacked at 5 mm intervals and the test method can be found in Ref.[17]. The simulated mutual coupling values between the presented tag antennas are compared with that of the traditional SRR antennas in free space. The results in Fig.14 show that the simulated coupling between two proposed tag antennas is lower than that of two traditional SRR antennas. Besides, the mutual coupling of the proposed antenna is less than −10 dB when two tags stacked at 5 mm intervals, which indicates the metal cabinet environment has no obvious effect on the tag and the tag is well isolated from the others.

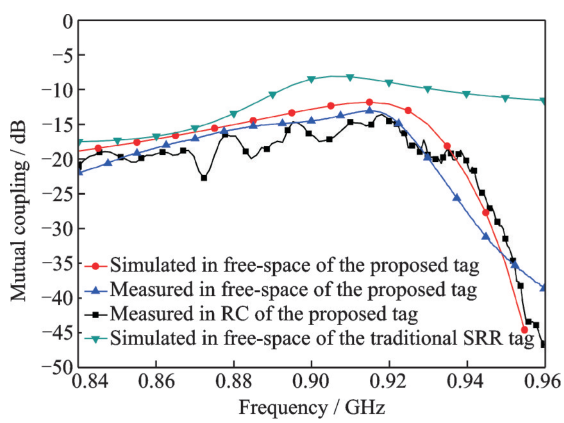


Fig.14 Mutual coupling between two identical tag antennas stacked at 5 mm intervals measured in free space and RC

4 Conclusions

A compact antenna formed by three concentric split rings for UHF RFID tag is presented. The principles of the traditional SRR antenna and the proposed antenna are explained. The size of the presented antenna is 83% smaller than that of the traditional SRR antenna while the gain remains moderate. The impedance, gain, maximum read range, efficiency, and mutual coupling of the proposed antenna are investigated. The simulated and measured results show that the presented antenna can cover the whole UHF RFID operating frequency band. Moreover, the tested maximum read range of the tag is in good agreement with the simulated results and can reach 45 cm in free space and 37 cm under dense tag environment. The mutual coupling between two stacked tag antennas is relatively low, which makes the tag operate reliably in practical applications.

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Author Contributions Mr. **CHEN Weikang** complied the models, interpreted the results and wrote the manuscript. Dr. **NIU Zhenyi** designed the study and conducted the analysis. Ms. **LI Mengyuan** contributed data and model components for the tag model. Dr. **XU Qian** provided the experiment environment. Prof. **GU Changqing** administrated the project. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Huangqun)

一种用于射频识别标签的改进开口环谐振器天线

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摘要：设计了一种由3个同心开口环构成的用于特高频(Ultra-high frequency, UHF)射频识别(Radio frequency identification, RFID)标签的小型化天线。该天线包括1个外部由传统开口环谐振器(Split-ring resonator, SRR)天线改进而成的短路环和1个SRR型加载结构，因此该天线可以看作一个内部加载SRR的短路环。根据传输线理论，为了与标签芯片的容性输入阻抗相匹配，采用短路环所需的环长比传统SRR天线的开路环结构短$\lambda_g/4$，由此设计的天线比基于传统SRR结构的天线更加紧凑。其后，采用ANSYS公司的高频结构仿真(High-frequency structure simulator, HFSS)软件对所设计的天线进行了仿真与优化。在混响室中测试了所加工的天线的阻抗、效率和互耦。结果表明，本文天线的谐振频段能够覆盖整个特高频射频识别的工作频段(840～960 MHz)，且尺寸比传统SRR天线减小83%。在自由空间和密集标签环境中测量所得的标签最大读距分别为45 cm和37 cm。

关键词：射频识别；小型化天线；开口环谐振器；混响室；密集标签环境