Chipless tag detection and recognition based on frequency modulated continuous wave

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Abstract. Towards the commercialization of chipless radio frequency identification (RFID) systems, there are still some pressing issues. The detection and identification of chipless RFID tags are mainly realized by a vector network analyzer (VNA). In practice, this equipment is costly and not convenient enough. This paper designs a maneuverable detection model based on frequency modulated continuous wave (FMCW), the detection target is an 8-bit chipless tag based on a variable-side-length spiral resonance unit and decodes the amplitude and phase information. On this basis, signal processing is performed on the generated amplitude and phase based on the Savitzky-Golay (SG) smoothing algorithm, and then the simulation data of HFSS is compared with ADS model data by the matrix pencil method (MPM). The results show that the proposed FMCW-based method can be effectively implemented in wireless communication, providing a new solution for flexible and inexpensive chipless tag detection and recognition.

1. Introduction

Radio Frequency Identification (RFID) is a technology that uses RF signals to identify specific tags and read related data. It has been applied to vehicle management, fare collection systems, logistics system, etc [1]. Chipless RFID is an emerging specific application technology with traditional optical barcodes, low cost without chip RFID tags, and its application is universal [2]. However, there are still some serious challenges in realizing the identification of chipless tags in real applications. It requires a more complex reading and writing system than traditional RFID. Chipless tags can generally be divided into two types, tags based on time-domain (TD) and frequency domain (FD) coding [3]. TD-based tags express encoded data through the amount of delay between backscattered signals, and the detection time to the reader requires nanoseconds, which is difficult to implement and insufficient encoding capacity [4]. Based on FD-encoded chipless tags are more stable, with higher coding density and low cost, and are easier to achieve miniaturization [5].

In terms of chipless tag detection and recognition technology, the prophase decoding method used is to detect the characteristic shape of the key frequency. From the literature [6], through a passive metamaterial-based quadrature phase-shift keying (QPSK) modulation chipless tag integrated with the partial discharge sensor, the detection and recognition of partial discharge are realized. On the other hand, FMCW radar can achieve target detection, ranging, and positioning [7]. For multiple metal tags, FMCW radar can identify and detect the corresponding tags and have relatively high signal strength. In radar or chipless RFID systems, the target pole is one of the important data in target recognition [4]. The electromagnetic scattering transient response of a chipless tag is the theoretical basis of the singularity expansion method (SEM), which provides a convenient way to analyze the post-response...
of the natural frequency scatter [8]. Chipless tags do not contain integrated circuits or a special metal structure of the chip, which can extract the poles through the scattering characteristics of the electromagnetic wave incident on the chipless tag. To realize the identification of the chipless tag, the MPM has strong noise suppression and data processing capabilities. Singular value decomposition (SVD) technology is used to suppress the influence of noise on the accuracy of poles [9], and it has been widely used in pole extraction method.

This paper designs a method for detecting and recognizing the coding information of chipless tags based on FMCW. Through the design of 8-bit chipless tags based on the frequency domain, the analysis of readers based on the FMCW method, and the combination of chipless tag data, and through simulation and analysis verified the feasibility of this method.

2. Chipless RFID tag design

2.1. Discussion of spiral resonant unit

The basic structure of the spiral resonant unit is shown in Figure 1(a).

![Figure 1](image1.png)

(a) The basic structure of the spiral resonance unit. (b) Equivalent circuit diagram of spiral resonance unit. (c) Equivalent circuit diagram of microstrip line coupled spiral resonator.

The spiral resonator can be equivalent to a quarter wavelength (\(\lambda/4\)) double-ended open-circuit resonator with a bent structure. The \(LC\) equivalent circuit is shown in Figure 1(b). Among them, \(R\) is the resistance, \(L\) is the distributed inductance, and \(C\) is the parasitic capacitance. As shown in Figure 1(c), \(L_m\) is the coupling inductance between the spiral resonance unit and the microstrip line. Combine the above circuit analysis, from the literature [10], the resonant frequency of the spiral resonator is calculated as follows:

\[
f_i = \frac{1}{2\pi\sqrt{L_iC_i}}
\]

Among them \(L_i\) is the total inductance value, \(C_i\) is the total capacitance value.

| Table 1. Main design length parameters. |
|----------------------------------------|
| length | W | \(L_1\) | s | m | n | d | g | l | h |
| Value(mm) | 5.5 | 7.3 | 0.7 | 15 | 15 | 0.5 | 0.2 | 2.45 | 0.8 |

For the spiral resonator in Figure 1(a) using RT/duroid®5880 dielectric substrate, the relative permittivity \((\varepsilon_r)\) is 2.2, the loss tangent \((\tan\delta)\) is 0.0009. The main parameters are as shown in Table 1. Use HFSS software for design simulation, as shown in Figure 2(a), the transmission characteristic \(S_{21}\) curve of the spiral resonator when the side length is changed from 5mm to 8.5mm according to the step length of 0.5mm, and the other parameters are unchanged as shown in Table 1. It can be seen that as the side length \(L_n\) increases, the resonant frequency of the spiral resonator becomes smaller. Therefore, changing the length of the side length \(L_n\) of the spiral resonator can significantly change the resonant frequency. The depth of the depression of the \(S_{21}\) curve has changed, so choose a suitable one for the following. The \(L_m\) parameter provides a reference to form a more robust chipless tag.
As shown in Figure 2(b), the resonance characteristics when the structural parameter gap $g$ change and the other parameters are unchanged as shown in Table 1. When $g$ changes between 0.1mm and 0.5mm, the resonance frequency is the largest the offset is 85MHz, indicating that there is almost no effect on the resonance frequency; when $g$ is greater than 0.4mm, the depth of the depression of the $S_{21}$ curve becomes shallow, indicating that the coupling is weakened, and the resonance frequency is slightly larger; when $g$ is less than 0.4mm, the coupling effect is strengthened; the depression depth of the $S_{21}$ curve is deepened, and the sensitivity is increased.

![Figure 2](image)

Figure 2. (a) The relationship between the side length and frequency of a single spiral resonant unit. (b) The amplitude change curve of the resonance point when the gap $g$ changes.

2.2. Chipless tag structure

![Figure 3](image)

Figure 3. (a) The layout of an 8-bit chipless RFID tag using a microstrip line. (b) $S_{21}$ curve of different ID information tags.

By arranging multiple spiral resonator units with different side lengths ($L_n$) on both sides of the 50Ω microstrip line, multiple notches are obtained in the working frequency band. Taking the above factors into account, a chipless tag with an 8-bit capacity is designed. Figure 3(a) shows the front structure, and the back is a grounding plate. The specific side length $L_n$ parameters of 8 spiral resonator units are shown in Table 2, and other parameters for spiral resonators are not changed. The dielectric substrate is RT/duroid®5880 (the high $h$ = 0.8 mm, long $m$= 43.8 mm, width $n$ = 17.45 mm).

| Table 2. Side length $L_n$ parameter. |
|--------------------------------------|
| $L_1$ | $L_2$ | $L_3$ | $L_4$ | $L_5$ | $L_6$ | $L_7$ | $L_8$ |
| Value(mm) | 7.3 | 6.8 | 6.3 | 5.8 | 5.3 | 4.9 | 4.6 | 4.3 |

In the HFSS software, the $S_{21}$ curve obtained by the finite element method (FEM), as shown in Figure 3(b), at 3.0GHz, 3.24GHz, 3.45GHz, 3.72GHz, 4.07GHz, 4.37GHz, 4.62GHz, and each of the 8 frequency points of 4.99GHz forms a notch structure. The minimum size of the $S_{21}$ of each beat is
larger than -20 dB; less than 400MHz between adjacent notch bandwidth; the quality factor (Q factor) is high. Each frequency points to the presence or absence are determined that the code is "0" or "1". The bands in the range of 2.5 to 5.5 GHz are divided into 8 segments, every 400MHz, make each resonance point fall into a different segment, thus reducing the mutual interference between the resonance points, and can easily change the bits to adapt to the data coding.

3. Chipless tag detection based on FMCW

3.1. The working principle and structure of chipless RFID reader

As shown in Figure 4(a), the working principle of signaling the tag is described. When the tag is inquired with an ultra-wide band (UWB) signal, the signal received (Rx) antenna captured the resonator to resonate and generate an amplitude attenuation. Each resonator acts as a strip-resistant filter, thereby generating phase hopping at each resonant frequency. Then, this signal retires back from the tag emission (Tx) antenna. The presence of the resonator causes the spectral amplitude attenuation and generates the phase jump, and the deletion of the resonator will neither the amplitude attenuation does not generate phase hopping.

If the response of the chipless tag in the frequency domain (TD) is \( H(f) \), the amplitude response \( A(f) \) and the phase response \( \phi(f) \) of the n-bit tag (if there is an n-resonator) may be represented by:

\[
A(f) = \prod_{n=1}^{N} |H_n(f)|
\]  \( (2) \)

\[
\phi(f) = \sum_{n=1}^{N} \angle H_n(f)
\]  \( (3) \)

Using equations (2) and (3), any frequency response of any chipless tag based on a multi-bit resonator can be described.

Figure 4(b) shows the block diagram of the reader based on FMCW. Coherent detection is realized through the bistatic FMCW radar architecture with two transmit and receive antennas. The digital part, including DAC, drives a voltage-controlled oscillator (VCO), Control and process the signal from the chipless tag. The following is a discussion of the signals of the various parts of the reader, use the equation to explain the reader’s detection of chipless tags.

Linear chirp signals as an inquiry signal of this reader. Sawtooth wave generator and a VCO generate linear chirp signals, The instantaneous frequency of sawtooth wave 11 can be expressed as:

\[
f(t) = f_c + Kt
\]  \( (4) \)

Where \( K \) is the frequency modulation slope:

\[
K = \frac{BW}{T_c}
\]  \( (5) \)

\( f_c \) is the starting frequency of the scan signal, \( BW \) is the bandwidth of the transmitted signal, and \( T_c \) is the duration of the sawtooth wave. Therefore, the signal of the signal generator is:

\[
S_c(t) = A_c \cos \left[ 2\pi \int_0^t (f_c + Kt')dt' \right] = A_c \cos(2\pi f_c t + \pi Kt^2)
\]  \( (6) \)

Suppose that the antenna has a linear response to the input sweep signal, and the efficiency is about
100%, then the transmitted signal \( S_{Tx}(t) \) can be approximated as \( S_c(t) \), that is, \( S_{Tx}(t) \approx S_c(t) \). The signal output from the coupling port of the coupler is \( S'_c(t) = k_1 S(t) \), where \( k_1 \) is the coupling coefficient.

Assuming that there is no phase and amplitude distortion at the transmitter and receiver in this process, and there is a constant path loss \( L_r \) in the working frequency range, and the time delay introduced by propagation between them is \( \tau_1 \). Then the signal received by the antenna is:

\[
S_{Rx}(t) = L_r A(f') A_c \cos \left[ 2\pi f_c(t - \tau_1) + \pi K(t - \tau_1)^2 + \phi(f') \right]
\]

(7)

among them, \( f' \) is the normalized time-varying phase of the sent interrogation signal, then:

\[
f'(t) = f_c t + \frac{K \tau_1^2}{2}
\]

(8)

Then the intermediate frequency (IF) signal is:

\[
S_{IF}(t) = S'_c(t) = k_1 \left[ \cos(\theta_1 + \theta_2) + \cos(\theta_1 - \theta_2) \right]
\]

\[
\theta_2 - 2\pi f_c (t - \tau_1) + 2\pi K (t - \tau_1) + \phi(f') \right]
\]

(9)

The intermediate frequency signal passes through a low-pass filter (LPF) and then filters out related high-frequency components. The output signals \( S(t) \) can be approximated as:

\[
S(t) \approx k_2 A(f') \cos \left[ 2\pi \frac{B_W}{T_c} \tau_1 t + 2\pi f_c \tau_1 + \phi(f') \right]
\]

(10)

Therefore, by analyzing the final output signal \( S(t) \), the tag information carried by the two functions \( A(f) \) and \( \phi(f) \) can be recovered, and the encoded data bits can be identified.

### 3.2. Structure Simulation of Chipless Tag Reader Based on FMCW

Figure 5 shows the model of the reader system designed on ADS2020 platform.

**Figure 5. Simulation model of the chipless reader on ADS2020 platform.**

Table 3 shows the parameters of the model in Figure 5. In this simulation model, a chirp signal generator is used, and its operating frequency is 2~6GHz. The chirp duration \( (T_c) \) is 500ns. For 8-bit chipless tags, working in a frequency bandwidth of 2~6GHz and had two monopole antennas loaded by discs. The S parameter file (s2p file) extracted by HFSS is connected to the VCO, mixer, coupler, and low-pass filter (LPF) in the schematic diagram of ADS to complete the RF part of the chipless reader. The received signal is amplified to better identify the information on the tag.

| Symbol | Description       | Value      |
|--------|-------------------|------------|
| \( f_c \) | Center frequency | 4 GHz      |
| \( B \)  | Bandwidth         | 4 GHz      |
| \( G_r \) | Antenna gain      | 20dB       |
| \( P_{tx} \) | Transmit power   | 20dBm      |
| \( T_c \) | Sweep time        | 500ns      |
Figure 6(a) shows the output signal of the TPA point in Figure 5, and using MATLAB, through the analysis signal \( S(t) \) based on Savitzky-Golay (SG) smoothing algorithm, the time domain of the tag response curve. The 8 resonance information corresponding to the 8 spiral resonance units can be roughly detected, but the resonance frequency information cannot be completely identified.

Figure 6(b) shows the phase angle of \( S(t) \) output by the SG algorithm. The 8 phase fluctuations introduced by the band-stop filter produced by the spiral resonator can be identified in the figure. The information at this stage can also be used to encode the data on the chipless tag.

However, the detection data is more accurate and reliable through the combination of amplitude and phase, and 8-bit chipless tags can be decoded as "11111111". In summary, it can be inferred that ADS2020 simulation and SG algorithm signal processing using MATLAB have verified the feasibility of the FMCW-based chipless RFID reader architecture.

### 4. Recognition of chipless RFID tags

In the chipless RFID system, pole data is one of the important parameters for multi-tag identification. The pole distribution extracted by the matrix pencil method (MPM) from the HFSS simulation data, and the ADS simulation model data is shown in Figure 7(a). The number of poles corresponds to the number of resonators, and the frequency points distributed by the poles are the same, and the positions of the same frequency points do not coincide. This is due to the coupling between adjacent resonators, resulting in the attenuation factor (residue) not equal.

| Frequency point | HFSS data extraction frequency | ADS data extraction frequency | Error |
|----------------|-------------------------------|-----------------------------|-------|
| 1              | 3.022                         | 3.032                       | 0.01  |
| 2              | 3.244                         | 3.254                       | 0.01  |
| 3              | 3.453                         | 3.462                       | 0.009 |
| 4              | 3.725                         | 3.733                       | 0.008 |
| 5              | 4.073                         | 4.078                       | 0.005 |
| 6              | 4.377                         | 4.381                       | 0.004 |
| 7              | 4.619                         | 4.628                       | 0.009 |
| 8              | 4.988                         | 4.996                       | 0.008 |

It can be seen from Figure 7(a) that the pole distribution of the chipless tag extracted by MPM is the 8 frequency points corresponding to the imaginary part of the pole. Compare the frequency points extracted from the HFSS simulation data with the ADS simulation model data, as shown in Table 4. As shown, the maximum contrast error is 0.01GHz; the minimum contrast error is 0.009GHz, which can achieve the recognition effect of chipless tags.

Perform the least-squares linear fitting on the data in Table 4, and the fitting result is shown in Figure 7(b). The fitting equation is:
where $x$ is the identified frequency value, $a = 0.99847$, $b = 0.1392$, the goodness of fit (Adj. R-square) is approximately equal to 0.99999, which indicates that the linear fit is relatively good, so it meets the accuracy requirements of chipless tag identification. In summary, the pole data extracted by the MPM can be encoded, and the discrete data can be processed to reduce the hardware cost of the reader.

![Graph](image)

Figure 7. (a) The pole distribution of chipless tag. (b) Frequency point linear fitting.

5. Conclusion
This paper designs a flexible chipless RFID coding tag detection model based on FMCW. The detection object is an 8-bit chipless tag, and the signal is encoded by the generated notch. The simulation verification was carried out in ADS, and the simulation experiment proved the feasibility of the system in solving the problem of chipless tag detection and recognition. In practical applications, it is more economical than traditional vector network analyzer detection methods. Although this method is feasible as a reader, there are still some challenges for designing a chipless tag reader. Later, specific experiments will be used to verify the feasibility of the proposed system, combining actual application needs and further developing in a suitable and convenient direction.

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