Design of millimeter-wave chipless tag based on variable angle arc resonator

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Abstract. Faced with the development of miniaturization and compactness of chipless radio frequency identification (RFID) tags, and to reduce the cost of traditional chip tags, this paper proposes a miniaturized, polarization-insensitive, passive, and chipless based on a variable-angle arc resonator. Chipless tags have a high coding density of 44.44 bits/cm² in the frequency range of 20GHz~31GHz, and a coding capacity of 4.04 bits/cm²/GHz. The patch on the substrate determines the signature of each resonant frequency, thereby determining the number of identification data bits. To accommodate more data bits and pass barriers between resonant features, the metal patches are orthogonally polarized so that adjacent resonant features will not interfere with each other. As the mm-Waves ultra-wideband (UWB) chipless tags, it can be easily printed on various IoT applications and has great potential for low cost and identity verification. This work makes it easier to implement highly robust, inexpensive, and flexible chipless tags for IoT applications in the mm-Wave band.

1. Introduction

Since the introduction of IoT systems, there has been an increasing demand for identification, perception, and tracking. RFID is a wireless data-acquisition technique extracting encoded data from a remotely placed tag [1]. The RFID system mainly includes RFID tags encoding data and an RFID reader for reading tags, where the reader consists of an antenna, a digital portion, and a radio portion. Chipless RFID is an emerging specific application technology with traditional optical barcodes, low cost without chip RFID tags, and its application is universal [2].

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]. Surface Acoustic Wave (SAW) tags based on the TD are the only commercially available chipless tags. However, the piezoelectric material of this type of tag requires sub-micron-level lithography technology, and the cost is comparable to that of traditional chip tags. There is no advantage over [5]. Chipless tags based on the FD can increase the encoding density [6], and encode by changing the frequency spectrum through the structure of the resonator. The encoding capacity depends upon the number of resonators. It can be seen from the above analysis that in the process of designing chipless RFID tags, achieving high spatial data density and high-performance compactness is still an important research direction.

One advantage of the mm-Wave band is that low-cost automotive frequency modulated continuous wave (FMCW) radar can be used as a chipless tag reader [7]. Automotive radar is very suitable in this
application because it not only meets the requirements of large-bandwidth encoded data but also meets
the effective method of locating tags and extracting their ID and data sensors. Many off-the-shelf FMCW
automotive radars can achieve this goal in the 24GHz and 79GHz frequency bands, thus realizing a very
cheap chipless RFID system. There are four main considerations for designing chipless tags in an mm-
Wave environment, namely, the use of low-cost substrates with maximum backscatter (because the final
tag can be detected by the reader), and high encoding capacity (thus making the tag size minimize) to
make the label read and write directions independently and label flexibility. The traditional tag and the
tag provided in the literature cannot meet all these requirements at the same time, but it involves a
compromise between the two. This article explains how the proposed variable-angle arc-based tag
overcomes the common problems mentioned above.

The purpose of this research is to design a fully printable mm-Wave passive chipless tag for low-cost
items. The operating frequency will be centered at 25GHz, and its frequency range will be within 20-
31GHz. The designed tag will contain at least 10bit data, and the data type will be in the frequency
signature domain.

2. Chipless RFID tag structure and working principle

2.1. Discussion of basic resonant unit

In this paper, a multi-resonator-coded tag is designed. This tag is formed by a plurality of variable-angle
circular arc resonators and a substrate. For chipless tags based on frequency domain characteristics, the
multi-patch structure used to store information is the key to the tag, and a specific structure is used to
generate a specific resonant frequency.

The arc patch-type basic resonant unit is designed by FEKO software. Its basic structure is shown in
Figure 1(a). The substrate material is selected as F4BM220 (dielectric constant \( \varepsilon_r=2.2 \), loss tangent is
\( \tan\delta=0.0007 \), thickness \( h=0.5\text{mm} \)). The resonant frequency of an arc is determined by its arc length \( L \),
and the calculation relationship is as follows:

\[
L = \frac{\alpha \pi R}{180}
\]

If a variable-angle arc resonator is loaded on the F4BM substrate, the resonant frequency is a function
of the arc length \( L \) of the resonator, where \( R \) is the radius of the arc, \( L \) is the arc length of the arc, and \( \alpha \)
is the number of central angles (angle system). Figure 1(b) The resonance response of an Electro-
Magnetic (EM) tag is mainly affected by three main parameters: \( R \), \( W \), and \( \alpha \). The over-etching and
under-etching provided by manufacturing errors will affect the size of the metal traces of each tag, which
will cause different frequency responses. The resonant frequencies caused by the two hypothetical
manufacturing structures can be seen in Figure 1(b), where \( \Delta_c \) represents the geometric changes caused
during the manufacturing process. Then, two tags with the same manufacturing mask may be affected
by different changes \( \Delta_1 \) and \( \Delta_2 \). These changes will change the resonant frequency. The larger the error
\( \Delta_e \), the smaller the width of the resonant unit and the higher the resonant frequency makes the entire
response sensitive to these changes.

![Figure 1](image)

Figure 1 (a) The basic structure of the variable-angle arc resonant unit. (b) The arcs with different
errors \( \Delta_1 \) and \( \Delta_2 \) applied during the manufacturing process lead to different EM responses of the tag.
The main factors affecting the resonant response of the chipless tag are discussed. The first is the influence of the central angle $\alpha$ on the resonant frequency. Choose $R=3.5\text{mm}$ and $W=0.5\text{mm}$ unchanged for simulation. The results are as follows as shown in Figure 2. The fitting formula is:

$$y = k \cdot \alpha^b$$

In the formula, $\alpha$ is the central angle, $k = 1629.75573 \pm 14.84127, b = -0.94698 \pm 0.00252$, and the goodness of fit (Adj. R-square) is approximately equal to 0.9999, indicating that the resonant unit and $\alpha$ change in a power function with a negative exponent. As $\alpha$ becomes larger, the resonance frequency becomes smaller.

![Figure 2](image)

Figure 2 The fitting curve of the influence of circle center angle $\alpha$ on resonance frequency.

The second is the influence of the arc width ($W$) on the resonance frequency. Choose $\alpha=90^\circ$ and $R=3\text{mm}$ unchanged for simulation. As shown in Figure 3(a), the resonance characteristics when the $W$ changes, when $W$ changes between $0.1\text{mm}$ and $0.6\text{mm}$, the maximum deviation for the resonance frequency is $2.2845\text{GHz}$, the minimum offsets are $0.3607\text{GHz}$, indicating that it has a greater impact upon the resonance frequency. As the $W$ increases, the radar cross-section (RCS) also increases. To make the resonant frequency higher, the structure with a smaller $W$ is more suitable for the realization of the expansion of the tag's coding capacity and the compact structure.

Next is the influence of the arc radius ($R$) on the resonance frequency. Choose $\alpha=90^\circ$ and the $W=0.2\text{mm}$ unchanged for simulation. Figure 3(b) shows the resonance characteristics when the $R$ changes. When $R$ changes from $2.5\text{mm}$ to $3.1\text{mm}$, the maximum deviation of the resonance frequency is the shift is $4.97\text{GHz}$, and the minimum shift is $0.6814\text{GHz}$, indicating that it has a greater impact on the resonance frequency. As the $R$ increases, the RCS also increases. The smaller the $R$, the smaller the occupied area, which is conducive to the miniaturization of the tag design. Through the analysis of each parameter, it provides a reference for selecting suitable parameters later, so that a more robust chipless tag can be formed.

![Figure 3](image)

(a) The amplitude change curve at the resonance point when the width $W$ changes.

(b) The amplitude change curve at the resonance point when the radius $R$ changes.
2.2. Chipless tag structure and working principle

It can be seen from the previous section that the frequency of the basic resonant unit based on the arc patch is closely related to its $L$. By changing $R$, $\alpha$, and $W$ to change the size of $L$, different resonant frequencies can be constructed. The basic structure of the chipless tag based on the variable-angle circular arc resonator is shown in Figure 4. The substrate material is selected as FR4B220. Although there is no suitable equivalent circuit to represent the resonant characteristics of this tag, there are distributed inductances in the metal part and distributed capacitance between metals.

As shown in Table 1 and Table 2, the parameters of the chipless tag structure, the width of the arc ($W$), and the gap ($d$) between them are selected to be 0.1mm and 0.1mm, respectively. In the FEKO simulation environment, the effects of $W$ and $d$ on the RCS level were studied respectively. The results show that, at the expense of a larger surface area, a wider arc can be used to obtain a higher tag RCS. Therefore, try to choose $W$ as small as possible to make a compact tag. Besides, $d$ will not significantly affect the RCS level of the tag.

![Figure 4 Basic structure of chipless tag based on the variable angle arc resonator.](image)

| length | $R_1$ | $R_2$ | $W$ | $m$ | $n$ | $d$ | $g$ | $l_1$ | $l_2$ | $h$ | $s_1$ | $s_2$ |
|--------|-------|-------|-----|-----|-----|-----|-----|-------|-------|-----|-------|-------|
| Value(mm) | 2 | 3.8 | 0.1 | 4.5 | 5 | 0.1 | 0.2 | 0.3 | 0.41 | 0.5 | 1.07 | 0.22 |

| angle | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ | $\alpha_6$ | $\alpha_7$ | $\alpha_8$ | $\alpha_9$ | $\alpha_{10}$ |
|-------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| value | 86° | 87° | 88° | 89° | 90° | 92° | 94° | 97° | 102° | 106° |

To increase the encoding capacity of chipless tags, multiple scattering units with different arc angles can be designed on the tag, and the nesting of the arc-shaped scattering units is adopted, so that the coding capacity is increased without increasing the tag area, which increases the information density of the tag. Place 10 arc patches with different radians on the tag, as shown in Figure 4, the minimum arc angle is $\alpha_1=86^\circ$ and the maximum is $\alpha_{10}=106^\circ$. In FEKO, through the Method of Moments (MoM), using the plane wave as the excitation source, using the far-field solution, the simulation obtained the backscatter response. In the online polarization mode, they are all excited by a plane wave with an electric field perpendicular to the substrate. As shown in Figure 5, it can be seen that the scattering response of 10 resonators will produce 10 resonance peaks in the frequency domain.
The surface current density is shown in Figure 6. To confirm the influence of each variable angle arc-shaped structure in the resonance frequency, the highest and lowest frequencies (20.09 and 30.68 GHz) were selected to draw the current distribution diagram. It can be seen that the highest frequency appears due to the resonant unit with the smallest arc length, while the resonant unit with the largest arc length gives the maximum current at the lowest frequency. At each resonance point, the corresponding variable angle arc-shaped the surface current on the patch is the largest.

Figure 7 shows the basic principle of the chipless identification authentication process, which is mainly composed of a chipless tag that encodes data, a reader that reads the tag, and a database that stores the data of the chipless tag. The reader consists of an antenna, a digital part, and a radio frequency part composition. The process can be divided into two steps. The first step uses a chipless reader to detect chipless tags for database registration; the second step compares the given unknown test tags (tags to be verified) with the database. In the comparison phase, for comparison purposes, simple signal processing can be performed to perform time gating on the measurement. Then, the cosine similarity function is used as a similarity measure to compare the identity verification of the tag with the database. Due to the use of electromagnetic characteristics, these characteristics are not easy to be forged. The goal here is to design a chipless tag to ensure unique and unforgeable harmonic characteristics. Considering chipless tags at mm-Wave frequencies, the main disadvantage is low-level signals, but techniques to overcome this limitation will be proposed. The tag must provide the same signature in both authentication steps, and the forged tag has a different signature from the database.
3. Analysis of the characteristics of chipless RFID tags

3.1. Analysis of polarization angle of chipless tag

The simulation coding method is through peak coding. The resonator with the largest arc length \( L \) has the lowest resonant frequency and is used to encode the highest bit; the resonator with the smallest arc length \( L \) has the highest resonant frequency and is used to encode the lowest bit. Each resonant frequency has a crest and trough on the RCS curve. The crest is used to encode the logic state "1", and the absence of the corresponding crest indicates the logic state "0".

In the FEKO software, select the linear polarization mode, and analyze the RCS curve with the polarization angle \( \eta \) = 0° to 90° under the excitation of the plane wave with the incident angle of \( \theta = 0° \) and \( \varphi = 0 \), as shown in Figure 8(a). It can be seen that in different modes, the resonant frequency remains unchanged, and is not affected by the change of the polarization angle. Also, by changing the polarization angle, the RCS response amplitude of the chipless tag changes. It can be observed that the adjacent wave peaks have small changes, which makes the tag design polarization insensitive.

Figure 8(b) shows the RCS of the tag with different polarization angles at 24.1GHz, for 4 different polarization angles: 0°, 30°, 60°, and 90°. It can be seen from the figure that as the polarization angle increases, the lobe becomes wider and the directivity is weakened. A reverse directional lobe of less than -50dB is obtained. The polarization angle will affect the chipless tag. It is not too large, and the polarization is not very sensitive.

3.2. Code analysis of chipless tag

Analyze the two states of coreless ID: 0101010101 and 1111111111. Any bit of "1" indicates that the relevant patch is in the tag, and "0" means that the patch does not exist. In Fig. 4, when the 1, 3, 5, 7, and 9 resonant units are removed, the corresponding resonant frequencies in Fig. 9 are also removed.
Besides, more resonant units can be added to the design, but at the expense of tag size and coding density. The encoding combination can be achieved by adding and eliminating different patches, which will affect the corresponding frequency characteristics on the RCS curve. Observed from the RCS curve, due to the existence of short-circuit slots between the patches, the impact on adjacent frequencies can be neglected. Therefore, different encoding states can be obtained by changing the number of resonators. In this design, $2^{10}$ tags with different encoding IDs can be generated.

![RCS curve of different ID information tags.](image)

**Figure 9** RCS curve of different ID information tags.

Table 3: Comparison of parameters of proposed chipless RFID tags.

| Chipless tag Types   | Number of bits | Frequency range (GHz) | Tag size (cm$^2$) | Bit density (bits/cm$^2$) | Encoding capacity (bits/cm$^2$/GHz) |
|---------------------|----------------|-----------------------|------------------|--------------------------|--------------------------------------|
| C-folded dipole [8] | 5              | 2.5-6.5               | 3×5              | 0.33                     | 0.083                                |
| Ring resonator [9]  | 23.7           | 3.9                   | 3×3              | 2.6                      | 0.433                                |
| Hairpin resonator [10] | 40           | 4.7-5.5               | 5×6              | 1.33                     | 0.38                                 |
| L-Shaped [11]       | 16             | 4.5-6                 | 1.7×1.7          | 5.54                     | 1.582                                |
| Elliptical slot [12] | 10            | 3.6-15.6              | 2.28×1.6         | 2.74                     | 0.274                                |
| **This work**       | **10**         | **20-31**             | **0.5×0.45**     | **44.44**                | **4.04**                             |

Table 3 is a comparison table between the coreless tags reported in recent years and the tag parameters proposed in this paper. The tag proposed in this paper contains 10 resonators in an area of 4.5×5mm$^2$, which can achieve a data capacity of 10bit. The tag proposed in this paper is compact, highly robust, flexible, and polarization-insensitive. Compared with the tag designs listed, the proposed configuration has good performance and improved results. For example, this tag can be used in healthcare applications, by identifying people and objects and remotely monitoring the patient's posture, movement, and other health conditions.

### 4. Conclusion

In this paper, a variable-angle arc resonator is used to design a chipless RFID tag based on the frequency domain, and a 10-bit tag is designed. The size of the tag is 4.5mm×5mm, and the working frequency band is 20GHz–31GHz with 44.44bits/cm$^2$. The high coding density verifies the performance of its design. Although the size of the tag is not optimal, it has a good reference value for the design of chipless RFID tags. Combined with some miniaturization technologies, it is also possible to print tags of smaller size and larger capacity on the flexible substrate. It is possible to develop small chipless tags for the mm-Wave frequency band to be used in medical applications and more IOT places, and there are huge application potentials in the authentication and anti-counterfeiting of many low-cost item tags.
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