Design and Detection of Chipless RFID Tags Using Stepped Impedance Resonators with Short-circuited Ends

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Abstract
This paper proposes multimode stepped impedance resonators with short-circuited ends, and descriptions are also given for a detection method using electromagnetic probes and a method of code identification. The stepped impedance resonators are composed of multiple transmission lines with different characteristic impedances, and they can control higher-order mode resonance frequencies. Using their intrinsic properties, identification codes from a resonator can be systematically generated by introducing symmetric multimode stepped impedance resonators with short-circuited ends, and these codes can be identified by detecting the higher-order mode resonance frequency. The experimental results show that proposed resonators can be used in chipless RFIDs, which have the advantages of a small tag size, accurate code detection, and minimal effects from reflections from the environment.

Keywords: Stepped Impedance Resonator with Short-circuited End, Electromagnetic Field Probe, Higher-order Mode Resonance, RFID Tag, Code Assignment, Code Identification

1. Introduction
Chipless radio frequency Identification (RFID) tag has attracted intense interest and is expected to complement optical bar codes, which are ubiquitous in inventory and logistic services. Many types of chipless tags that use electromagnetic methods have been proposed, and numerous experimental results have already been reported.[1, 2] There are two techniques for such tags. In one method, a delay time is applied through delay lines using surface acoustic wave devices; in the other, resonance frequencies of multiple resonators are used.[3-6] The resonance frequency method is advantageous for increasing the number of codes generated and reducing cost. The chipless RFID tag considered in the present work is based on spectral information coding, the same as the conventional multi-resonator method. However, a key difference is the number of resonators used. The proposed method uses a single resonator with higher-order resonance frequencies that can be controlled by changing its structure such as conductor width and line length.

Passive bandpass filters with wider stop band characteristics or multiple passbands using stepped impedance resonators have been developed to control higher-order resonance frequencies.[7-9] Additionally, multi-resonator chipless RFID tags using stepped impedance resonators have been reported.[10] However, stepped impedance resonators with multiple sections or multiple steps have not been a focus of research. We proposed and reported the tags using stepped impedance resonators with open-circuited ends.[11, 12]

In this paper, we propose the tags using short-circuited stepped impedance resonators, which are rarely used as resonant elements because they require through vias and their resonance characteristics are degraded by stray components generated near via holes. Furthermore, the method of detecting the tag resonance frequencies is examined by using our electromagnetic field probes.[12]

Firstly, the general structure of stepped impedance resonators with an arbitrary number of sections and short-circuited ends is introduced and the resonance conditions and higher-order mode resonance frequencies are examined. Secondly, code assignment to the resonator structure and code identification using resonance frequencies are discussed by introducing the concept of code distance. Thirdly, the detection method for multimode resonance frequencies using the electromagnetic field probes is
described. This method will contribute to size reduction of tags and tag readers. Fourthly, experimental tags and probes are designed for verifying the properties of chipless tags using multimode stepped impedance resonators with short-circuited ends. Finally, the experimental results are presented and discussed.

2. Short-Circuited Stepped Impedance Resonator

2.1 Basic structure of resonator

Figure 1 shows the basic schematic of multimode stepped impedance resonators with multi-section transmission lines and open-circuited ends or short-circuited ends. These resonators have symmetric structures composed of two composite transmission lines. The lines comprise cascaded connections of transmission lines \( T_i (i = 1, \ldots, N) \) with characteristic impedance \( Z_i \) and common electrical length \( \theta \).

The resonator of electrical length \( \theta = \pi / 2 \) has a singular resonance point, regardless of the characteristic impedance values and their combination, and it can be regarded as an \((N/2)\)-wavelength resonator. There are \( N \) resonance points below this singular resonance point, and so this resonator can be treated as a multimode resonator. We define the singular resonance frequency as the reference frequency, \( f_N \).

The resonance conditions of a multimode stepped impedance resonator with open-circuited ends (Fig. 1 (a)) have been reported by analyzing input admittance.\[11, 12\] The resonance conditions of a multimode stepped impedance resonator with short-circuited ends can be derived by considering input impedance. It is assumed that \( Z_{Nk} \) expresses impedance at the point of symmetry from one of the short ends of the resonator, and that \( Z_{ik} \) indicates impedance at the point of connection between the \( k \)th and \((k - 1)\)th transmission lines, counting from the short end of the resonator (Fig. 2).

For simplicity, ignoring stray capacitance generated at the step junctions, the resonator impedance, \( Z_{TN} \), at the symmetry point can be expressed as a recurrence relation:

\[
Z_{TN} = Z_{N0} / 2
\]

\[
Z_{N0} = Z_N (Z_{N-1} + jZ_n \tan \theta) (Z_N + jZ_{N-2} \tan \theta)
\]

\[
Z_{Nk} = Z_k (Z_{k-1} + jZ_k \tan \theta) (Z_k + jZ_{k-1} \tan \theta)
\]

\[
Z_{N2} = Z_2 (Z_1 + jZ_1 \tan \theta) (Z_1 + jZ_1 \tan \theta)
\]

\[
Z_{N1} = jZ_n \tan \theta.
\]

Based on equation (1), \( Z_{N0} \) is expressed as

\[
Z_{N0} = jZ_N (A_N / B_N) = jZ_N \tan \theta (A_N / B_N)
\]

where

\[
A_N = a_{0N} + a_{2N} \tan^2 \theta + \cdots + a_{2(N-1)} \tan^{2(N-1)} \theta
\]

\[
B_N = b_{0N} + b_{2N} \tan^2 \theta + \cdots + b_{2(N-1)} \tan^{2(N-1)} \theta.
\]

The coefficients \( a_{2N} \) and \( b_{2N} \) are functions of the transmission line’s characteristic impedance ratio, \( R_Z \), and are expressed as

\[
a_{2N} = R_{2N}^{-1} (b_{2N-1} + a_{2N-1})
\]

\[
b_{2N} = R_{2N}^{-1} b_{2N-1} - a_{2(k-1)N-1}
\]

where

\[
a_{01} = b_{01} = 1, \quad a_{21} = b_{21} = 0
\]

\[
R_{2N}^{-1} = Z_{k-1} / Z_k \text{ (impedance ratio)}.
\]

Resonance conditions can be obtained by considering the following two cases.

\[ B_N \rightarrow 0 \text{, with odd higher-order mode resonance} \]

\[ A_N' \rightarrow 0 \text{, with even higher-order mode resonance} \]

We denote the \( i \)th-order mode resonance frequency as \( f_i \), and the corresponding electrical length as \( \theta_i \). We introduce the normalized frequency \( F_i \), which is the value obtained by dividing \( f_i \) by the reference frequency \( f_N \). From this, the normalized frequencies are obtained as

\[
F_i = f_i / f_N = \theta_i / \theta_N = (2 / \pi) \cdot \theta_i
\]

where

\[
\theta_0 = \pi / 2
\]

\[
F_N = f_N / f_N = \theta_N / \theta_N = 1.0.
\]

3. Code Assignment and Identification

3.1 Code assignment to multimode stepped impedance resonators

The discussion in Section II shows that the higher-mode resonance frequencies of multimode stepped impedance
resonators can be varied by changing their structure, as for the open-circuited stepped impedance resonator.[11] Conversely, the resonator structure can be uniquely identified by detecting the higher-mode resonance frequency. This observation can be applied to RFID tags by assigning codes to stepped impedance resonator structures.[12] The multimode stepped impedance resonator has a structure consisting of a transmission line, $T_k$, whose characteristic impedance levels are restricted to the $m$ levels of the discrete values $Z_a, Z_b, \ldots, Z_m$, as shown in Fig. 3. Because there are $N$ transmission lines, the resonator should have $mN$ structures. Thus, $mN$ distinct codes can be assigned to these stepped impedance resonator structures. However, stepped impedance resonators with the same impedance level become uniform transmission line resonators, and their higher-order resonance frequencies are identical. Therefore, it is necessary to avoid assigning codes to $m$ structures of these stepped impedance resonators, and the number of possible codes to be assigned is $mN - m + 1$. The number of impedance levels, $m$, can be set more than 4, so $mN$ becomes larger than $2^N$, which is the number of codes of a conventional multi-resonator tag with $N$ resonators.

3.2 Code distance

To discuss stepped impedance resonator codes systematically, code tables that contain the calculated resonance frequency data for the stepped impedance resonators are used. Higher-mode resonance frequencies of the stepped impedance resonator shown in Fig. 2 can be treated as coordinate positions of $N$-dimensional normalized frequency space.[12] The coordinates of code $#i$ and $#j$ can be expressed as $(F_{i1}, F_{i2}, \ldots, F_{IN})$ and $(F_{j1}, F_{j2}, \ldots, F_{jN})$, respectively, and we define code distance between code $#i$ and $#j$ as

$$D_d(i,j) = \sqrt{(F_{i1} - F_{j1})^2 + (F_{i2} - F_{j2})^2 + \cdots + (F_{IN} - F_{jN})^2}. \quad (6)$$

For code assignment, it is necessary to set $D_d(i,j)$ as large as possible, and it is desirable to avoid code assignment for small values of $D_d(i,j)$.

3.3 Code identification

Figure 4 shows a basic system diagram of the chipless tag reader, which is composed of a transmitter, receiver, frequency detector, code detector, and code table. The transmitter acts as the interrogator for the tags and transmits the frequency sweep signals or the impulse signals to the chipless tags from the Tx port. Reflected signals from the tags are received by the receiver, resonance frequencies are detected by the frequency detector, and then tag codes are identified by the code detector looking up the code table.

The coordinates of the code obtained from the code table are different from each other; therefore, they can be used to identify the code of chipless tags. For code identification, the ID code can be determined by searching for a minimum code distance between the measured and detected coordinate positions, which are obtained from the detected normalized resonance frequencies and the code table. The coordinate of code $#x$, which corresponds to the detected tag, can be expressed as $(F_{x1}, F_{x2}, \ldots, F_{xN})$, and the code distance between codes $#i$ and $#x$ is expressed as

$$D_m(i,x) = \sqrt{(F_{i1} - F_{x1})^2 + (F_{i2} - F_{x2})^2 + \cdots + (F_{IN} - F_{xN})^2}. \quad (7)$$

The measured tag code is identified by searching for the minimum value of $D_m(i,x)$ obtained from equation (7). The minimum value is zero when there is no error between the designed and measured higher-mode resonance frequencies. However, it is difficult to realize the resonance frequencies of multimode stepped impedance resonator precisely as designed. Thus, the minimum value is not generally zero. To improve code identification, plural code distances can be used between the code of interest and other codes. These multiple code distances are unique combinations for the code of interest, and can be distinguished from other codes by the calculating the difference for each code distance. We define the code-distance difference as

$$E(i,j) = |D_m(i,x) - D_d(i,j)|. \quad (8)$$

$E(i,j)$ can be treated as the error between the designed
and measured code distance. We can identify the measured code by calculating several values of $E(i,j)$. This method will be discussed in detail in relation to the experimental data.

4. Resonance Frequency Detection Circuit

4.1 Frequency detection by electromagnetic field probes

To identify a tag code, the resonance frequencies must be detected. Conventional chipless tags are generally composed of resonators and two antennas (Tx and Rx), and resonators are usually implemented together with the antennas in the same substrate.[1]

Figure 5 shows the chipless tag and the frequency detector proposed here. A tag consists of a U-shaped multimode stepped impedance resonator with short-circuited ends and is much smaller than a conventional chipless tag with two antennas. To detect the resonance frequencies of this tag, an exciter and a detector using magnetic field probes are introduced. Conventional electromagnetic probes are usually composed of lumped element capacitors or inductors. Even though lumped element probes are small, their frequency responses are not suitable for wideband applications. In our approach, we use transmission line probes with short-circuited ends to detect the resonance frequencies of the multimode stepped impedance resonator with short-circuited ends. The coupling circuit is created by two transmission lines at the short-circuited end portions of the stepped impedance resonator tag and probe. For multimode stepped impedance resonators with open-circuited ends, electric field probes are also used to detect resonance frequencies. These probes are set close to the open-circuited and short-circuited ends of the stepped impedance resonator for excitation and detection of the resonator, and they are hardly affected by multiple reflections from the environment. Therefore, the detection area is limited to less than several millimeters, but this allows for reduced size and improved detection accuracy.

4.2 Equivalent circuit of the frequency detector

The detection circuit using electromagnetic probes shown in Fig. 6 is the resonator-coupled two-port network; therefore, the equivalent circuit with symmetrical coupling can be constructed as shown in Fig. 6. The transmission loss, $L(\omega)$, of this circuit near each higher-order resonance frequency can be calculated by [13]

$$L(\omega) = \left\{ (2 + Q_e / Q_0)^2 \right\} / 4 \quad (9)$$

where

- $Q_0$: unloaded $Q$ of resonator
- $Q_e$: external $Q$ of resonator
- $\omega$: angular frequency
- $\omega_c$: angular resonance frequency.

The basic properties of the chipless tag using multimode stepped impedance resonator can be analyzed by equation (9).

4.3 Detection peak level and $Q$ value

The minimum value of transmission loss $L_0$, which corresponds to the detection peak level at resonance, can be obtained by substituting $\omega = \omega_c$ into equation (9) as follows.

$$L_0 = L(\omega_c) = 1 + (Q_e / Q_0) + (Q_e / Q_0)^2 / 4 \quad (10)$$

$Q_0$ and $Q_e$ are derived from equation (9) and (10) as

$$Q_0 = (1 / \omega_c) \left( 1 - 1 / \sqrt{L_0} \right) \quad (11)$$

$$Q_e = (1 / \omega_c) \cdot 2 \sqrt{L_0} \quad (12)$$

where

- $\omega_c$: angular frequency at 3 dB increase points from $L_0$ ($\omega_1 < \omega_c, \omega_2^2 = \omega_c / \omega_1$).
- $L_0$ = $L(\omega_1) = L(\omega_2)$ = $L_0 + Q_e^2 (\Omega_c)^2 / 4$. $\Omega_c$ is the relative 3 dB bandwidth, and it can be expressed by equations (11) and (12) as

$$\Omega_c = 1 / Q_0 + 2 / Q_e \quad (13)$$

Equation (10) shows that to decrease the transmission loss, a large $Q_0$ value and small $Q_e$ value are required. To detect the resonance frequency accurately, a detector with a narrow frequency resolution should be used. Therefore, a detector with a small relative 3 dB bandwidth, $\Omega_c$, is required, meaning that large values of $Q_0$ and $Q_e$ are also required.

Fig. 5 Detection method using the magnetic field probe.

Fig. 6 The equivalent circuit of the frequency detector.
necessary, as shown by equation (13). Thus, the requirements for the $Q_e$ value are contradictory. However, the $Q_e$ value can be controlled over a wide range by the coupling conditions between the probes and the tag resonator, and the optimum value can be determined through these equations and experiments.

5. Design of the Chipless Tags and Probes

5.1 Chipless tags

Experimental multimode stepped impedance resonators were designed and fabricated to verify their basic characteristics. The resonators are composed of 10 transmission lines ($N = 5$), in which the number of characteristic impedance levels is $m = 4$ (a: $Z_a = 40\, \Omega$; b: $Z_b = 65\, \Omega$; c: $Z_c = 120\, \Omega$; d: $Z_d = 160\, \Omega$), and reference frequency $f_5$ is set as $5.0\, \text{GHz}$. In this case, it is expected that $m^N - m + 1 = 1,021$ distinct codes will be generated, as described above. Eight types of tags were designed using multimode stepped impedance resonators with short-circuited ends, and their calculated resonance frequencies are shown in Table 1.

Code numbers are assigned to correspond to the transmission line combinations, such as bbbbb or abcd. The resonator structure with code bbbbb is a uniform transmission line resonator with a characteristic impedance of 65 Ω.

The calculated code distances, $D_{ij}(i,j)$, of the stepped impedance resonators with short-circuited ends are shown in Table 2. The value of $D_{ij}(i,j)$ is closely related to the code identification. To discuss the limitations of code identification, we use a small code distance value using code bbbba and ccccb as an example pair, for which $D_{ij}(i,j)$ has small values of 0.0130 for stepped impedance resonators with short-circuited ends.

Higher-order resonance frequencies of multimode stepped impedance resonators are determined by impedance ratio $R_Z$. For stepped impedance resonators with codes bbbba and ccccb, the values of $R_Z$, and $R_Z$ are 1.00, and the values of $R_Z$ are 1.625 ($= Z_b/Z_a$) and 1.846 ($= Z_c/Z_b$) for codes bbbba and ccccb, respectively. Therefore, the multimode resonance frequencies of the stepped impedance resonators are close, and code distance $D_{ij}(i,j)$ becomes small.

### Table 1 Code table (stepped impedance resonators with short-circuited ends).

| Code          | Normalized resonance frequency | Resonance frequency (GHz) |
|---------------|-------------------------------|---------------------------|
|               | $F1$  | $F2$  | $F3$  | $F4$  | $F5$  | $f1$  | $f2$  | $f3$  | $f4$  | $f5$  |
| bbbbbb(s1)    | 0.2000 | 0.4013 | 0.6000 | 0.8013 | 1.0000 | 1.0001 | 2.0063 | 3.0001 | 4.0066 | 5.0000 |
| bbabb(s2)     | 0.1952 | 0.3591 | 0.5902 | 0.8546 | 1.0000 | 0.9759 | 1.7957 | 2.9512 | 4.2731 | 5.0000 |
| bbbaa(s3)     | 0.1799 | 0.4277 | 0.5727 | 0.8186 | 1.0000 | 0.8995 | 2.1387 | 2.8637 | 4.0931 | 5.0000 |
| ccccb(s4)     | 0.1731 | 0.4345 | 0.5653 | 0.8233 | 1.0000 | 0.8655 | 2.1723 | 2.8265 | 4.1164 | 5.0000 |
| abcd(s5)      | 0.2731 | 0.4546 | 0.6071 | 0.8040 | 1.0000 | 1.3657 | 2.2732 | 3.0355 | 4.0202 | 5.0000 |
| dcbaa(s6)     | 0.1301 | 0.3933 | 0.6308 | 0.8009 | 1.0000 | 0.6504 | 1.9664 | 3.1542 | 4.0047 | 5.0000 |
| abcba(s7)     | 0.1812 | 0.5038 | 0.6225 | 0.7732 | 1.0000 | 0.9062 | 2.5191 | 3.1126 | 3.8660 | 5.0000 |
| cbabc(s8)     | 0.1804 | 0.2956 | 0.6257 | 0.8209 | 1.0000 | 0.9020 | 1.4778 | 3.1283 | 4.1046 | 5.0000 |

### Table 2 Code distance $D_{ij}(i,j)$ (stepped impedance resonators with short-circuited ends).

| Code $j$ (designed) | bbbbbb | bbabb  | bbbaa  | ccccb  | abcd   | dcbaa  | abcba  | cbabc  |
|---------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| bbbbbb(s1)          | 0.0000 | 0.0688 | 0.0464 | 0.0593 | 0.0909 | 0.0768 | 0.1103 | 0.1122 |
| bbabb(s2)           | 0.0688 | 0.0000 | 0.0809 | 0.0881 | 0.1343 | 0.0997 | 0.1697 | 0.0816 |
| bbbaa(s3)           | 0.0464 | 0.0809 | 0.0000 | 0.0130 | 0.1040 | 0.0858 | 0.1016 | 0.1424 |
| ccccb(s4)           | 0.0593 | 0.0881 | 0.0130 | 0.0000 | 0.1120 | 0.0913 | 0.1032 | 0.1516 |
| abcd(s5)            | 0.0909 | 0.1343 | 0.1040 | 0.1120 | 0.0000 | 0.1575 | 0.1098 | 0.1858 |
| dcbaa(s6)           | 0.0768 | 0.0997 | 0.0858 | 0.0913 | 0.1575 | 0.0000 | 0.1252 | 0.1118 |
| abcba(s7)           | 0.1103 | 0.1697 | 0.1016 | 0.1032 | 0.1098 | 0.1252 | 0.0000 | 0.2137 |
| cbabc(s8)           | 0.1122 | 0.0816 | 0.1424 | 0.1516 | 0.1858 | 0.1118 | 0.2137 | 0.0000 |
Experimental multimode stepped impedance resonators with short-circuited ends were fabricated by using microstrip lines on a substrate with a thickness of 0.508 mm and a relative dielectric constant of 2.20 (Rogers RT/Duroid 5880). Figure 7 shows a photograph of the experimental tags. The size of an individual tag is 60 × 20 mm, although the size can be reduced by using a thin substrate with a high dielectric constant.

5.2 Electric and magnetic field probes

Frequency detection by using electric field probes has been reported briefly;[12] however, the detailed characteristics of the probes have not been discussed. To obtain more information about this detection method, we prepared electric field probes and magnetic field probes for detecting the frequency of stepped impedance resonators with open-circuited-ends and short-circuited ends, respectively.

Figure 8 shows the experimental electric and magnetic field probes for tag code detection. The substrate material of the probes is the same as that of the experimental tags, and the probe size is 40 × 30 mm.

6. Experiments

6.1 Electromagnetic field probes

Prior to the detailed measurement of the experimental tags, the basic properties of the probes were measured.

These experiments for the probes and tags were carried out using an XYZ movable stage (Fig. 9).

In the measurements, the X-, Y-, and Z-axis correspond to the coupling line length (L), offset from the line center (δℓ), and coupling line spacing (S), respectively. The chipless tags used for probe measurements are uniform transmission line resonators with open-circuited ends (o1) and short-circuited ends (s1) (Fig. 10). The characteristic impedance, the line length and the line width of these resonators are 65 Ω, 111.6 mm and 1.01 mm, respectively.

Coupling length L affects the detection level, which reaches its maximum when electrical coupling is 90°. Considering the detection bandwidth, we set the coupling length as 10 and 15 mm. Initially, we examined the range of external Q (Qₑ) values obtained with these probes and tags.

Figure 11 shows the measured Qₑ values obtained by changing coupling line spacing S. This data shows that the Qₑ value can be controlled over a wide range and that these properties are suitable for the probe. In addition, the unloaded Q (Q₀) values of the measured tags with short and open circuited ends are identical and approximately 170.

Next, we measured the characteristics of the electric and magnetic field probes. Figs. 12(a) and 12(b) show the frequency responses of tags o1 and s1 with four values of S.
as parameters, with coupling length $L$ of 10 mm and offset $\delta l$ of 0 mm. Detection signal levels in these figures correspond to transmission losses between the exciter and the detector probe in the tag measurement. These data show that the detection peak levels become high at resonance frequencies where $S$ is small, although the resonance frequencies are shifted downward for tag t1 and upward for tag s1. These characteristics are caused by tighter coupling between the probe and tag resonator when $S$ becomes smaller.

These responses show that there are more attenuation points in Fig. 12(b) than in Fig. 12(a). These attenuation poles are generated by stray coupling between the short-circuited transmission lines of the exciter and detector probe. Therefore, the stray coupling of the magnetic field probe is more than that of the electric field probe. Stray coupling strength is determined by special layout of the probe strip lines and can be reduced by layout optimization.

Figure 13 shows the detection peak levels as a function of $S$. The values of slope of the detection level at resonance frequencies in the vicinity of $S = 2$ mm have frequency dependence, but these values are almost constant in the case of the magnetic field probe, but slightly change in the case of the electric field probe. The detection distance of the magnetic probe, which corresponds to the maximum line spacing, $S$, is 5 mm, which is slightly longer than that of the electric field probe. Figure 14 shows the resonance frequency shift from the proper values, which corresponds to resonance frequency with less influence of the probe, as a function of line spacing, $S$. For the electric field probe, the resonance frequencies are shifted upward as $S$ increases, and these frequency changes are large in comparison with the magnetic field probe. In the magnetic field probe, the frequency change is in the opposite direction.
tion, and the degree of change is small at 1% or less when $S$ is at least 1 mm.

The results in Figs. 13 and 14 show that the detection range in which the frequency can be accurately measured is 2–4 mm for the electric field probe and 1–5 mm for the magnetic field probe. Thus, the method of detecting the resonance frequency of short-circuited tags with the magnetic field probe is superior to that of open-circuited tags with the electric field probe in the detection area.

Figures 15(a) and 15(b) show the effects of line offset $\delta l$ on frequency response. These data indicate that detection peak levels decrease as $\delta l$ increases, but that the resonance frequencies hardly change. The basic characteristics of the two probes are similar. Moreover, there is no problem with frequency detection for $\delta l$ of 1.5 mm or less.

6.2 Frequency responses of chipless tags

Frequency responses of the experimental tags were measured based on the experimental results of the probes. Figure 16 shows some of the frequency responses of the experimental tags containing stepped impedance resonators with short-circuited ends, respectively, with $S$ of 2.0 mm, coupling length $L$ of 15.0 mm, and line offset $\delta l$ of 0 mm.

Fig. 15(a) Effects of line offset $\delta l$ in the electric field probe.

Multimode resonances up to the sixth order are shown in the figures, and the attenuation poles, which were caused by stray coupling, are visible. The resonance frequencies of the fifth-order mode resonance, which corresponds to the reference frequency ($f_5$), are almost identical. The frequency responses in Fig. 16 are different and easy to distinguish, indicating that the correspondence between the frequency response and code can be obtained. $Q_0$ values of the stepped impedance resonators used in the tags are estimated from the frequency responses as 100–170 depending on the stepped impedance resonator structures, and stepped impedance resonators composed of transmission lines with low characteristic impedance have high $Q$ values. The range of $Q_0$ values is similar to that of stepped impedance resonators with open-circuited ends [12] and there is little problem in frequency detection when the $Q_0$ value is 100 or more.

6.3 Measured resonance frequencies

The measured resonance frequencies and corresponding normalized resonance frequencies are summarized in Table 3 together with the designed values. These data show that the designed and measured resonance frequencies agree well in the third or higher resonance modes, but errors of around 3% between the frequencies are observed for some codes in the first and second resonance modes; for example, $F_2$ of code abcba(s7). The main cause of these errors is the manufacturing accuracy of the characteristic impedance of transmission lines.

6.4 Code identification

Code distance $D_m(i,x)$ of the stepped impedance resonator tags with short-circuited ends is shown in Table 4. The minimum values of the code distance are along the diagonal in the table (highlighted), where the measured and designed codes match. Thus, the experimental resonator codes can be uniquely identified by using the code dis-
In designing the experimental tags, we prepared code bbbba and ccccb as examples that may be difficult to identify. We can identify the measured code s4 as ccccb by searching the minimum value in the figure, but the margin for identification is not sufficient. Because the minimum value is 0.0035 and the next smallest value is 0.0118, and the ratio of these values is only 3.4.

To improve the code distance method, we introduced the difference of code distances, $E_{ij}(i,j)$, defined in equation (8). We used this method to identify whether the measured code $x(s4)$ is bbbba or ccccb. The case of two codes is discussed here, but even in the case of three or more codes, this method can be applied by successively comparing the two codes. Figs. 17(a) and 17(b) show the designed code distances, $Dm(i,bbba)$ and $Dd(i,cccb)$, respectively. The measured code distance, $Dm(i,x)$, is shown in Fig. 17(c). The code distances in the three figures are similar, but we can identify them by calculating $E_{ij}(i,j)$, and we define $E_1(i)$ and $E_2(i)$ as

$$E_1(i) = E(i,bbba) = |Dm(i,x) - Dd(i,bbba)|$$

$$E_2(i) = E(i,cccb) = |Dm(i,x) - Dd(i,cccb)|.$$  

Figure 18 shows the calculated data for $E_1(i)$ and $E_2(i)$. Measured code x can be identified as code ccccb because $E_1(i) > E_2(i)$ in all codes. To examine, the coincident index, $CI(i)$, quantitatively, it is defined as

| Table 3 | Measured resonance frequencies of the short-circuited tags. |
|---------|----------------------------------------------------------|
| Code    | Resonance frequency (GHz) | Normalized resonance frequency |
|         | $f_1$ | $f_2$ | $f_3$ | $f_4$ | $f_5$ | $F_1$ | $F_2$ | $F_3$ | $F_4$ | $F_5$ |
| bbbba(s1) | 0.994 | 2.020 | 3.001 | 4.012 | 5.002 | 0.199 | 0.404 | 0.600 | 0.802 | 1.000 |
|          | (1.000) | (2.000) | (3.000) | (4.000) | (5.000) | (0.200) | (0.400) | (0.600) | (0.800) | (1.000) |
| bbabb(s2) | 0.969 | 1.810 | 2.951 | 4.255 | 4.979 | 0.195 | 0.364 | 0.593 | 0.855 | 1.000 |
|          | (0.979) | (1.799) | (2.966) | (4.276) | (5.000) | (0.196) | (0.360) | (0.593) | (0.855) | (1.000) |
| bbbba(s3) | 0.895 | 2.147 | 2.867 | 4.099 | 4.993 | 0.179 | 0.323 | 0.574 | 0.821 | 1.000 |
|          | (0.899) | (2.138) | (2.862) | (4.101) | (5.000) | (0.179) | (0.323) | (0.574) | (0.821) | (1.000) |
| ccccb(s4) | 0.859 | 2.144 | 2.815 | 4.095 | 4.964 | 0.173 | 0.322 | 0.567 | 0.825 | 1.000 |
|          | (0.870) | (2.170) | (2.830) | (4.130) | (5.000) | (0.174) | (0.324) | (0.567) | (0.826) | (1.000) |
| abcdd(s5) | 1.321 | 2.262 | 3.021 | 3.998 | 4.997 | 0.264 | 0.453 | 0.605 | 0.800 | 1.000 |
|          | (1.363) | (2.279) | (3.037) | (4.013) | (5.000) | (0.273) | (0.456) | (0.607) | (0.803) | (1.000) |
| dcbba(s6) | 0.671 | 1.981 | 3.134 | 3.979 | 4.979 | 0.135 | 0.389 | 0.629 | 0.799 | 1.000 |
|          | (0.648) | (1.969) | (3.161) | (4.010) | (5.000) | (0.130) | (0.394) | (0.632) | (0.802) | (1.000) |
| abcba(s7) | 0.907 | 2.420 | 3.084 | 3.884 | 4.997 | 0.182 | 0.484 | 0.617 | 0.777 | 1.000 |
|          | (0.904) | (2.519) | (3.103) | (3.857) | (5.000) | (0.181) | (0.504) | (0.621) | (0.771) | (1.000) |
| cbabc(s8) | 0.902 | 1.481 | 3.086 | 4.075 | 4.954 | 0.182 | 0.299 | 0.623 | 0.823 | 1.000 |
|          | (0.898) | (1.471) | (3.133) | (4.110) | (5.000) | (0.180) | (0.294) | (0.627) | (0.822) | (1.000) |

(Designed values shown in the parentheses)

| Table 4 | Code distance $Dm(i,x)$ (short-circuited end stepped impedance resonator tags). |
|---------|------------------------------------------------------------------|
| Code    | Code i (designed) |
|         | bbbba | bbabb | bbbba | ccccb | abcd | dcbba | abcb | cbabc |
| s1(bbbba) | 0.0300 | 0.0687 | 0.0440 | 0.0569 | 0.0908 | 0.0759 | 0.1087 | 0.1137 |
| s2(bbabb) | 0.0676 | 0.0049 | 0.0788 | 0.0860 | 0.1326 | 0.0977 | 0.1667 | 0.0839 |
| s3(bbbba) | 0.0481 | 0.0817 | 0.0036 | 0.0119 | 0.1039 | 0.0859 | 0.1003 | 0.1440 |
| s4(cccccb) | 0.0577 | 0.0850 | 0.0118 | 0.0035 | 0.1122 | 0.0894 | 0.1048 | 0.1488 |
| s5(abcdd) | 0.0830 | 0.1289 | 0.0959 | 0.1041 | 0.0088 | 0.1493 | 0.1034 | 0.1805 |
| s6(dcbba) | 0.0718 | 0.0984 | 0.0806 | 0.0864 | 0.1513 | 0.0607 | 0.1189 | 0.1141 |
| s7(abcba) | 0.1067 | 0.1651 | 0.0962 | 0.0974 | 0.1066 | 0.1234 | 0.0069 | 0.2111 |
| s8(cbabc) | 0.1084 | 0.0767 | 0.1383 | 0.1475 | 0.1820 | 0.1101 | 0.2107 | 0.0050 |
\[ CI(i) = +1 \quad : \quad DE(i) > 0 \\
= -1 \quad : \quad DE(i) < 0 \\
= 0 \quad : \quad DE(i) = 0 \]

where \( DE(i) = E_1(i) - E_2(i) \)

The probability factor of coincidence, \( PF \), is expressed as

\[ PF = \left( \sum CI(i) \right) / k \]

where \( k \) is the number of designed codes.

\( PF \) takes a value between −1 and +1, and the measured code \( x \) can be identified as ccccb or bbbba when \( PF > 0 \) or \( PF < 0 \), respectively. For \( PF = 0 \) the measured code cannot be determined. Calculated values of the related data are shown in Table 5, and in these experiments, \( PF \) is calculated from the table as

\[ PF = \left( \sum CI(i) \right) / k = 8 / 8 = 1.00. \]

The measured code is identified as ccccb with the highest probability. The probability of identification can be improved by applying this method together with method of searching for the minimum code distance, \( Dm(i,x) \).

### 7. Conclusion

We proposed multimode stepped impedance resonators with short-circuited ends and a method for detecting their resonance frequencies by using magnetic probes for chipless RFID tags. In addition, we proposed a method of code identification using multiple code distances. Experimental tags and probes were designed and fabricated to verify our method. The results showed that the basic characteristics, such as detection area and accuracy of frequency detection, were superior to those of stepped...
impedance resonators with open-circuited ends, and that identification of the resonator codes was improved by using multiple code distances and searching for the minimum code distance. Proposed chipless RFID tag system has a small tag size and accurate code detection that is hardly affected by reflections from the environment. Future work will include reducing the size and cost of tags and increasing number of codes that can be generated.

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