A study on a coding method for chipless RFID tags using multimode stepped impedance resonators

Fuminori Sakai\(^{1, a)}\), Mitsuo Makimoto\(^1\), and Koji Wada\(^2\)

\(^1\) Sakura Tech Corporation, 301A West, Kanagawa Science Park, 3–2–1 Sakado, Takatsu-ku, Kawasaki 213–0012, Japan

\(^2\) The University of Electro-Communications, 1–5–1 Chofugaoka, Chofu, Tokyo 182–8585, Japan

\(^a\) sakai@sakuratech.jp

**Abstract:** Stepped impedance resonators (SIRs) are composed of multiple transmission lines having different characteristic impedances, and can control higher-order mode resonance frequencies. Here, by using these properties, identification codes from a resonator were systematically generated by introducing symmetric multimode SIRs composed of same-length transmission lines. In the other direction, resonator codes were identified by detecting their higher-order mode resonance frequencies. This paper describes these resonance properties and experimental results from multimode SIRs, and discusses their applicability in chipless RFID tags.

**Keywords:** stepped impedance resonator, higher-order mode resonance, RFID tag, bar code, UWB

**Classification:** Microwave and millimeter wave devices, circuits, and systems

**References**

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1 Introduction

Management systems that use bar code identification tags have been widely adopted in applications such as inventory and logistics services. Tag systems offer notable advantages, particularly extremely low cost because the tags themselves are made by printing on paper. However, conventional bar code systems have some drawbacks as well, including easy tampering, lack of confidentiality, and low reliability. Moreover, one pressing problem is that the detection area is narrow and code detection is interrupted by obstacles.

To overcome these drawbacks of bar coding, chipless RFID tags that use electromagnetic methods have been proposed [1, 2], and it is well-known that there are typical two techniques for such tags. In one method, a delay time is applied through delay lines using SAW devices [3]; in the other, resonance frequencies of multiple resonators are adopted [4, 5, 6, 7]. The latter method is better on amount of code generation and cost. The chipless RFID tag considered here operates on the basis of spectral information coding, the same as in the conventional multi-resonator method. However, a key difference is the number of resonators used. The proposed method uses a single resonator that can control higher-order resonance frequencies by changing its structure.

Bandpass filters with a wide stop band [8] and triple-band bandpass filters using stepped impedance resonators (SIRs) [9, 10] have been developed for their ability to control higher-order resonance frequencies [11]. Additionally, multi-resonator chipless RFID tags using SIRs have been reported [12]. However, SIRs having multiple sections or multiple steps have not been a focus of research. Here, we introduce general structures of SIRs having an arbitrary number of sections and discuss the resonance conditions and higher-order mode resonance frequencies for application in chipless RFID tags.

2 Structure and resonance conditions

2.1 Basic structure of resonator

Fig. 1 shows the basic structure of a multimode SIR having multisection transmission lines of the type to be considered here. This resonator has a symmetric structure composed of two composite transmission lines. These lines comprise cascaded connections of transmission lines \( T_i \) \( (i = 1, \ldots, N) \) having characteristic impedance \( Z_i \) and common electrical length \( \theta \), as shown in the figure. The
The displayed resonator has two open-circuited ends, but short-circuited ends are also possible. The resonator of electrical length $\theta = \pi/2$ has a singular resonance point, regardless of characteristic impedance values and their combination, and 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 $f_N$.

### 2.2 Resonance conditions and resonance frequencies

The resonance conditions of a multimode SIR can be obtained by analyzing input admittance. It is supposed that $Y_{in}$ expresses admittance at the point of symmetry from one of the open ends of the resonator, and also that $Y_{ik}$ indicates admittance at the connecting point between the $k$th and $(k - 1)$th transmission line from the open end of the resonator. For simplicity ignoring stray capacitances generated at the step junctions, the resonator admittance $Y_{TN}$ at the symmetry point can be expressed by a recurrence relation as follows:

$$
Y_{TN} = 2Y_{in}
$$

$$
Y_{in} = Y_N(Y_{IN-1} + jY_N\tan\theta)/(Y_N + jY_{IN-1}\tan\theta)
$$

$$
\vdots
$$

$$
Y_{ik} = Y_k(Y_{ik-1} + jY_k\tan\theta)/(Y_k + jY_{ik-1}\tan\theta)
$$

$$
\vdots
$$

$$
Y_{i2} = Y_2(Y_{i1} + jY_2\tan\theta)/(Y_2 + jY_{i1}\tan\theta)
$$

$$
Y_{i1} = jY_1\tan\theta.
$$

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

- $Y_{TN} \rightarrow \pm \infty$: with fundamental and odd-order higher-mode resonance
- $Y_{TN} \rightarrow 0$: with even-order higher-mode resonance

To give a simple example, we discuss the case where $N = 3$. In this case, input admittance is obtained as follows:

$$
Y_{T3} = 2Y_{i3}
$$

$$
= 2Y_3(Y_2 + jY_3\tan\theta)/(Y_3 + jY_{i2}\tan\theta)
$$

$$
= j2Y_3 \cdot (A_3/B_3),
$$

where $A_3 = (1 + R_{Z1} + R_{Z1} \cdot R_{Z2} - R_{Z2}\tan^2\theta) \cdot \tan\theta$

![Fig. 1. Basic structure of multimode SIR](image-url)
Here, we denote the \(i\)-th order higher-mode resonance frequency as \(f_i\), and the corresponding electrical length as \(\theta_i\). We also introduce the normalized frequency \(F_i\), which is the value obtained by dividing \(f_i\) by the reference frequency \(f_N\). From this, the resonance conditions with \(N = 3\) are expressed as

\[
\tan^2 \theta_1 = \frac{R_{Z1} \cdot R_{Z2}}{(1 + R_{Z1} + R_{Z2})}
\]

\[
\tan^2 \theta_2 = \frac{(1 + R_{Z1} + R_{Z2})/R_{Z2}}{R_{Z1}}
\]

\[
\theta_3 = \pi/2.
\]

Consequently, the normalized frequencies are obtained as

\[
F_1 = f_1/f_3 = \theta_1/\theta_3 = (2/\pi) \cdot \theta_1
\]

\[
F_2 = f_2/f_3 = \theta_2/\theta_3 = (2/\pi) \cdot \theta_2
\]

\[
F_3 = f_3/f_3 = \theta_3/\theta_3 = 1.0.
\]

Input admittance and resonance conditions of multimode resonators in the general case can be also obtained as similar functions of \(\theta\) and the impedance ratio \(R_{Zk} = Z_k/Z_{k+1}\). In actual design, it is required to take the step discontinuities into consideration for determining resonance frequencies by circuit simulator.

3 Code assignment and tag configuration

From the above discussion, it is clear that multimode SIRs have the capability to vary their higher-mode resonance frequencies by changing structure. In the other direction, 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 SIR structures.

![Code assignment to multimode SIRs](Fig. 2. Code assignment to multimode SIRs)

It is now supposed that the multimode SIR 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 indicated in Fig. 2. Since there are \(N\) transmission lines, the resonator should have \(m^N\) structures. From this, \(m^N\) distinct
codes can be assigned to these SIR structures. However, SIRs having the same impedance level become uniform transmission line resonators, and their higher-order resonance frequencies are identical. It is therefore necessary to avoid assigning codes to these SIR structures. Number of the impedance levels \( m \) can be set to be more than 4, therefore \( m^N \) is much larger than \( 2^N \) which is number of codes of the conventional multi-resonator tag having \( N \) resonators.

In order to identify code of the SIR it is required to provide the code table which has the calculated resonance frequency data for all of the SIRs to be considered.

Higher-mode resonance frequencies of the SIR shown in Fig. 2 can be treated as a coordinate position of N-dimensional normalized frequency space.

The coordinates of code \( \#i \) and \( \#j \) can be expressed as \( (F_1,i, F_2,i, \ldots, F_N,i) \) and \( (F_1,j, F_2,j, \ldots, F_N,j) \), respectively, and we define code distance between code \( \#i \) and \( \#j \) as follows:

\[
D(i, j) = \sqrt{(F_1,i - F_1,j)^2 + (F_2,i - F_2,j)^2 + \cdots + (F_N,i - F_N,j)^2}.
\]

In the case of code assignment it is necessary to set \( D(i, j) \) as large as possible, and it is desirable to avoid code assignment for the very small value of \( D(i, j) \).

On the contrary, in the case of code identification it is possible to find out ID code by searching minimum value of code distance between the measured and designed coordinate positions which are obtained from the detected normalized resonance frequencies and the code table. Moreover, frequency resolution required for detector of resonance frequency can be discussed by considering code distance \( D(i, j) \).

Fig. 3 shows examples of RFID tag configuration using multimode SIRs. In the figure, (a) and (b) indicate the band-pass and band-reject frequency response, respectively. Wideband monopole antennas [13] can be used as transmitting (TX) and receiving (RX) antennas, and they are arranged orthogonally so as to separate the input and output signals of the tag [14]. These antennas and their spatial layout are commonly used in conventional RFID tags [1].

![Fig. 3. Examples of RFID tag configuration with frequency response (a) pass and (b) reject.](image-url)
4 Experiments

4.1 Design

In line with the discussion above, experimental multimode SIRs were designed and fabricated to verify their basic characteristics. The resonators are composed of six transmission lines ($N = 3$) in which the number of transmission line characteristic impedance levels is $m = 5$. For this case, it is expected that $m^N = 5^3 = 125$ distinct codes will be generated as described above. It is now supposed that each of the codes will be assigned to a resonator structure by providing the combinations of line impedances as indicated in Table I. In the case of assigning code in decimal, we represent impedance levels to integer coefficients as $Z_a \rightarrow 0$, $Z_b \rightarrow 1$, $Z_c \rightarrow 2$, $Z_d \rightarrow 3$ and $Z_e \rightarrow 4$, and then code $#k$ can be expressed as follows:

$$k = a_0 \cdot 5^0 + a_1 \cdot 5^1 + a_2 \cdot 5^2$$  \hspace{1cm} (10)

In the above equation $a_0$, $a_1$ and $a_2$ denote integer coefficient (0,1,2,3,4) corresponding to impedance level of Line T1, Line T2 and Line T3, respectively.

The impedance levels are specified as $Z_a = 30$, $Z_b = 40$, $Z_c = 50$, $Z_d = 60$, $Z_e = 70 \Omega$. Then, the normalized frequencies can be determined from the resonator structures that correspondent to each of the assigned codes, as shown in the table.

The periodic solutions can be obtained from Eqs. (3) and (4) for resonance conditions, after which the resonator structures can be identified by detecting $N$ successive higher-mode resonance frequencies. The resonator structure is checked to ensure that three higher-mode resonances are generated in the microwave ultrawide band (for Japan, this is 7.25–10.25 GHz). Consequently, the reference frequency $f_3$ is determined to be 3.4 GHz and the higher-mode frequencies to be detected are $f_7$, $f_8$, and $f_9$ ($= 10.2$ GHz). Seven types of SIR, denoted #000, #001, #004, #014, #110, #102, and #022, have been designed as indicated in Table I.

Table II shows the calculated values of code distance between the experimental SIRs. It can be seen from the table that the code distance between code #000 and #001 has the smallest value of 0.036. This value is normalized by reference frequency $f_3$ ($= 3.4$ GHz), therefore actual value can be considered as 122 MHz, and this value is corresponding to minimum frequency resolution required to frequency detector.

### Table I. Code table for the experimental SIRs

| Code No. Line Combination | Normalized Resonance Frequency | Detection Freq. (GHz) |
|---------------------------|--------------------------------|-----------------------|
|                           | $F_1$ | $F_2$ | $F_3$ | $F_7$ | $F_8$ | $F_9$ | $f_7$ | $f_8$ | $f_9$ |
| #000 Za Za Za             | 0.33  | 0.67  | 1.00  | 2.33  | 2.67  | 3.00  | 7.92  | 9.08  | 10.20 |
| #001 Zb Za Za             | 0.36  | 0.69  | 1.00  | 2.36  | 2.69  | 3.00  | 8.02  | 9.15  | 10.20 |
| #004 Ze Za Za             | 0.40  | 0.74  | 1.00  | 2.40  | 2.74  | 3.00  | 8.16  | 9.32  | 10.20 |
| #014 Zc Zc Za             | 0.41  | 0.65  | 1.00  | 2.41  | 2.65  | 3.00  | 8.19  | 9.01  | 10.20 |
| #110 Za Zc Ze             | 0.26  | 0.65  | 1.00  | 2.26  | 2.65  | 3.00  | 7.68  | 9.01  | 10.20 |
| #102 Zc Zc Ze             | 0.28  | 0.78  | 1.00  | 2.28  | 2.78  | 3.00  | 7.75  | 9.45  | 10.20 |
| #022 Zc Zc Zc             | 0.36  | 0.56  | 1.00  | 2.36  | 2.56  | 3.00  | 8.02  | 8.70  | 10.20 |
The experimental multimode SIRs are fabricated on a substrate with thickness of 0.5 mm and a relative dielectric constant of 3.85. Fig. 4 shows the photograph of them. Parallel coupled lines with coupling length of 4.0 mm and line spacing of 0.4 mm (#000, #001, #110, #102, ##022), and 0.7 mm (#004, #014) are used for the coupling circuit. The size of the individual multimode SIR is 100 mm × 10 mm. Size reduction of the SIR can be realized by using thin substrate and hairpin shaped layout of the resonator pattern.

| Code #i | #000 | #001 | #004 | #014 | #110 | #102 | #022 |
|--------|------|------|------|------|------|------|------|
| #000   | 0.000| 0.036| 0.099| 0.082| 0.073| 0.121| 0.114|
| #001   | 0.036| 0.000| 0.064| 0.064| 0.108| 0.120| 0.130|
| #004   | 0.099| 0.064| 0.000| 0.091| 0.166| 0.126| 0.184|
| #014   | 0.082| 0.064| 0.091| 0.000| 0.150| 0.184| 0.103|
| #110   | 0.073| 0.108| 0.166| 0.150| 0.000| 0.132| 0.135|
| #102   | 0.121| 0.120| 0.126| 0.184| 0.132| 0.000| 0.234|
| #022   | 0.114| 0.130| 0.184| 0.103| 0.135| 0.234| 0.000|

**Fig. 4.** Photograph of the experimental SIRs

### 4.2 Measured frequency responses

Fig. 5 shows the simulated and measured wide band frequency responses of the code #014. The multi-mode resonances up to the 11th-order are indicated in the
figure. Simulation has been carried out by assuming the substrate having relative
dielectric constant of 3.85, loss tangent of 0.01 and thickness of 0.508 mm, and it
can be said that good agreement with measured responses has been obtained.

\[
L(\omega) = \left\{ (2 + Q_e/Q_0)^2 + Q_e^2 (\omega/\omega_c - \omega_c/\omega)^2 \right\}/4
\]

where

- \( Q_0 \): unloaded-Q of resonator at respective resonance modes
- \( Q_e \): external-Q of resonator at respective resonance modes
- \( \omega \): angular frequency
- \( \omega_c \): angular resonance frequency.

\( Q_0 \) and \( Q_e \) are derived from equation (11) as [8],

\[
Q_0 = (1/Q_c)/(1 - 1/\sqrt{L_0}) \quad (12)
\]

\[
Q_e = (1/Q_c) \cdot 2\sqrt{L_0} \quad (13)
\]

where

- \( L_0 = L(\omega_c) \): transmission loss at resonance (\( \omega = \omega_c \))
- \( Q_e = (\omega_2/\omega_1 - \omega_1/\omega_c) = (\omega_2 - \omega_1)/\omega_c \) \quad (14)

\( \omega_1, \omega_2 \): angular frequency at 3 dB increase points from \( L_0 \)

\( \omega_1 < \omega_2, \omega_c^2 = \omega_1 \cdot \omega_2 \).
From the measured responses shown in Fig. 5 $Q_0$ and $Q_e$ values can be estimated. Table III shows calculated data at the resonance frequencies of the typical higher order modes. It can be seen that the variation of unloaded-Q values is small for all resonance modes. It seems that these Q-values are dominantly determined by loss tangent of substrate. The sharp frequency responses and increase of losses are observed at the lower order of higher mode resonances in the Fig. 5, and these characteristics are correspondent to higher external-Q values at this band. From equation (12) and (13), external-Q ($Q_e$) is expressed as,

$$Q_e = 2Q_0\sqrt{L_0 - 1}.$$  \hspace{1cm} (15)

In practical design, the range of $L_0$ value is given by tag system requirements at first, and afterward $Q_0$ and $Q_e$ should be discussed using equation (15).

**Table III.** Calculated unloaded-Q and external-Q

| Resonance Mode | Resonance Freq. (GHz) | Unloaded-Q $Q_0$ | External-Q $Q_e$ |
|----------------|-----------------------|-----------------|-----------------|
| $f_1$          | 1.324                 | 96              | 11200           |
| $f_3$          | 3.212                 | 94              | 4600            |
| $f_5$          | 5.105                 | 94              | 2380            |
| $f_7$          | 7.747                 | 93              | 2060            |
| $f_8$          | 8.535                 | 91              | 1660            |
| $f_9$          | 9.613                 | 90              | 1450            |

Amplitude and phase frequency responses at the detection band (UWB band) are shown in the Fig. 6. The resonance frequencies can be obtained by detecting the peaks of amplitude response and/or the maximum phase deviations of phase response near higher-mode resonance points. It becomes clear from the measured results that frequency resolution is below 10 MHz, which is much smaller than the required value of 122 MHz for identification of resonator codes in this experiment.

To distinguish $k$-th and $(k+1)$-th higher-order mode resonances, it is required that the frequency span between $k$-th and $(k+1)$-th resonance mode is larger than the 3 dB bandwidth of $i$-th order frequency response $\Delta f_k$, then

$$f_{k+1} - f_k > \Delta f_k.$$  \hspace{1cm} (16)

$\Delta f_k$ is expressed by using equation (12) and (14) as,

$$\Delta f_k = \Omega_e \cdot f_k = f_k \left(\frac{Q_0}{\sqrt{1 - 1/\sqrt{L_0}}}\right).$$  \hspace{1cm} (17)

Substituting equation (17) to (16), we obtain the following equation as,

$$Q_0 > \left(\frac{f_k}{(f_{k+1} - f_k)}\right)\sqrt{1 - 1/\sqrt{L_0}}.$$  \hspace{1cm} (18)

This equation shows the requirement for unloaded-Q to detect the multi-mode resonance frequencies separately. In the case of the code #014, the required unloaded-Q value of resonator is 11, which can be obtained from equation (18).
by substituting the values of $f_7$, $f_8$ and $L_0$. This value is much smaller than the measured Q value of 93. It can be said that SIR having high unloaded-Q value is very useful to distinguish the neighboring resonance peaks definitely.

Fig. 7 shows the frequency responses of the experimental SIRs at the detection band. It can be recognized from the figure that the resonance frequencies of the 9th-order higher-mode resonance, which is equal to three times the reference frequency ($f_3$), are almost identical. The measured resonance frequencies and the corresponding normalized resonance frequencies are summarized in Table IV together with the designed values.

Fig. 7. Frequency responses at the detection band
The measured resonance frequency data are shifted downward from the designed values because of an incorrect estimate for the dielectric constant of the substrate. However, the error rates of all measured frequencies to the corresponding designed frequencies are almost the same; therefore, there is little difference between the measured and designed resonance frequencies after normalization, which can be seen from the table. This means that resonance frequency shifts caused by dispersion according to the dielectric constant of the substrate and by temperature can be neglected during frequency normalization, and it can be said that this property is one feature of these multimode SIRs.

The data of code distance between the measured and designed code are shown in the Table V. Comparing the corresponding values of Table V and Table II, it can be recognized that there exist maximum difference value of 0.014 between them, however, the minimum value of code distance in the same row of Table V provides each of the resonator code to be determined. Thus the experimental resonator codes can be uniquely identified by using the code distance method.

### Table IV. Measured and designed resonance frequencies

| Code No. | Resonance Frequency (GHz) | Normalized Resonance Freq. |
|----------|---------------------------|-----------------------------|
|          | $f_7$  | $f_8$  | $f_9$ | $F_7$ | $F_8$ | $F_9$ |
| #000     | 7.47 (7.92) | 8.53 (9.08) | 9.59 (10.20) | 2.34 (2.33) | 2.67 (2.67) | 3.00 (3.00) |
| #001     | 7.57 (8.02) | 8.63 (9.15) | 9.60 (10.20) | 2.37 (2.36) | 2.69 (2.69) | 3.00 (3.00) |
| #004     | 7.68 (8.16) | 8.76 (9.32) | 9.57 (10.20) | 2.41 (2.40) | 2.75 (2.74) | 3.00 (3.00) |
| #014     | 7.74 (8.19) | 8.53 (9.01) | 9.61 (10.20) | 2.41 (2.41) | 2.66 (2.65) | 3.00 (3.00) |
| #110     | 7.23 (7.68) | 8.53 (9.01) | 9.61 (10.20) | 2.26 (2.26) | 2.66 (2.65) | 3.00 (3.00) |
| #102     | 7.32 (7.75) | 8.88 (9.45) | 9.56 (10.20) | 2.29 (2.28) | 2.79 (2.78) | 3.00 (3.00) |
| #022     | 7.56 (8.20) | 8.21 (8.70) | 9.57 (10.20) | 2.37 (2.36) | 2.57 (2.56) | 3.00 (3.00) |

(Designed values shown in parentheses)

### Table V. Code distance between measured and designed code

| Measured Code | #000 | #001 | #004 | #014 | #110 | #102 | #022 |
|---------------|------|------|------|------|------|------|------|
| A(#000)       | 0.010 | 0.028 | 0.092 | 0.073 | 0.082 | 0.125 | 0.112 |
| B(#001)       | 0.045 | 0.010 | 0.058 | 0.057 | 0.117 | 0.127 | 0.130 |
| C(#004)       | 0.113 | 0.078 | 0.014 | 0.100 | 0.180 | 0.133 | 0.196 |
| D(#014)       | 0.081 | 0.058 | 0.081 | 0.010 | 0.150 | 0.177 | 0.112 |
| E(#110)       | 0.071 | 0.104 | 0.161 | 0.150 | 0.014 | 0.122 | 0.141 |
| F(#102)       | 0.126 | 0.122 | 0.120 | 0.184 | 0.143 | 0.014 | 0.240 |
| G(#022)       | 0.108 | 0.120 | 0.173 | 0.089 | 0.136 | 0.228 | 0.014 |

5 Conclusion

In this paper, novel coding method using multimode SIRs were proposed for application in chipless RFID tags. The results show that it is possible to provide
resonator codes systematically from their independent structure and, in the other
direction, to identify the resonator codes by detecting their higher-order mode
resonance frequencies. As future work, wireless transmission experiments using
such tags equipped with transmitting and receiving antennas and size reduction of
multimode SIRs should be carried out.

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