Four-State Coupled-Line Resonator for Chipless RFID Tags Application

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Abstract: A novel quad-state coupled-line microstrip resonator is proposed for compact chipless radio frequency identification (RFID) tags. The proposed resonator can be reconfigured to present one of four possible states: 00, 01, 10, and 11, representing, no resonance, resonance at f_2 , resonance at f_1 , and resonance at both f_1 and f_2 , respectively. The frequency span between f_2 and f_1 can be easily controlled, thereby reducing the required spectrum. Moreover, the proposed technique allows the storage of a large amount of data in a compact size to reduce the cost per bit. A multi-resonator prototype consisting of six resonators is designed, analyzed, and experimentally characterized. This prototype is implemented on the RT Duroid 5880 substrate with a dielectric constant of 2.2, loss tangent of 0.0009, and thickness of 0.79 mm. The designed configuration can be reconfigured for 4^6 codes. Two complete the RFID tags, including the six resonators and two orthogonally polarized transmitting and receiving antennas, are implemented and tested. The first tag code is designed for all ones, 1111111111, and the second tag is designed as 1010101010 code. Experimental results show good agreement with the simulation.

Keywords: chipless RFID; retransmitted based; four-state resonator; ultra wide band (UWB) antenna; internet of things (IoT)

1. Introduction

In a radio frequency identification (RFID) system, radio frequency waves are used to read identification codes implemented on a tag. The main components of an RFID system include: An RFID transponder (a tag containing a sequence of electronic codes used for object identification), and an RFID reader (an interrogator that collects information from the tag) [1]. However, low-cost applications are still dominated by traditional barcodes rather than RFID tags, owing to the high prices of the latter [2]. Therefore, chipless RFID tags have recently attracted attention as a promising candidate to replace barcodes. The size and capacity of chipless RFID tags are among the main challenges for their cost reduction and thus wide adoption.

Different methods are reported in the literature for data encoding in chipless RFID tags. Generally, these encoding techniques can be classified into various domains, such as time, frequency, phase, and hybrid-domains [3]. In time-domain-based systems [4,5], the RFID reader interrogates the tag with a sequence of short pulses. Subsequently, the tag receives the interrogating pulses and then retransmits the response signal as a train of echoes with some time delays. The presence or absence of echoes and their position along the time axis are used to read out the tag ID. The surface acoustic wave (SAW) chipless RFID tag is the most popular and commercial time-domain-based chipless tag [6]. However, these tags are not recommended for cost-effective applications, owing to the high material costs and complex fabrication process. In frequency-based chipless RFID systems [7,8], the reader interrogates the tag with an electromagnetic (EM) waveform and then the tag retransmits (or backscatters) the response to the RFID reader. In the phase domain, differences in the phase profile

are used to encode the bits [9,10]. In hybrid-domain encoding techniques, more than one domain is used. These additional domains include phase–frequency [11,12], time–frequency [13], impedance loading [14], polarization–phase [15], and frequency–position [16]. However, as mentioned in [17], for a significant number of bits, hybrid-domain techniques still require a very high spectral bandwidth and the resultant configuration in this case will not be matched for low-cost readers.

Returning to frequency-domain chipless RFID systems, there are two different types of tags: Backscattering-based and retransmission-based. In the backscattering technique, the tag contains only resonating elements, where no separate antennas are required [18,19]. More advantages of this technique include the tag's small size and easier readability. However, adding more bits introduces coupling and affects the resonance frequency of the other units, and more calibration may be required to overcome this influence [20]. As shown in Figure 1, a retransmission-based chipless RFID tag consists of orthogonally polarized transmitting and receiving antennas and a sequence of n resonators (for an n -bit tag), in which the information is stored [1,21]. The presence or absence of a resonance is encoded as 1 (at which $S_{21} < -10$ dB) or 0, respectively. The resonators are always implemented with a microstrip structure; hence, its ground acts to minimize the effect of the object to which the tag is attached. In addition, this technique has a more stable performance because the use of two orthogonally polarized antennas significantly reduces the interference between the transmitted and received waves [20]. Moreover, the tag capacity can be increased by simply adding more resonators to the structure and the arising mutual coupling can be reduced by adjusting the distance between the resonators. Retransmission chipless RFID tags are based on stopband resonators. Stopband characteristics in the microstrip technique can be achieved by either directly connecting quarter-wave stubs to the feeder line [22–25], or by a short-circuited quarter-wave coupled line, as shown in Figure 2. The short circuit shown in Figure 2 can be replaced by another quarter-wave open-circuit stub to produce various forms of tags. Several chipless RFID tags have been developed based on these types of resonators, such as spiral resonators [26–30], open-loop resonators [31], L-strip shaped resonators [32], and complementary split-ring resonators (CSRR) [33]. An improved structure that combines a spiral and T-shaped coupled line in a compact form is proposed in [34]. Each resonator in these configurations is represented by only one bit; hence, an n -bit tag requires n resonators and produces 2^n codes.

Figure 1. Simple block diagram of retransmission chipless radio frequency identification (RFID) tag.

In this paper, a new coupled-line microstrip resonator is proposed for compact high-capacity chipless RFID tags. Each resonator can store either 00 (no frequency response), 01 (resonance at f_2), 10 (resonance at f_1), or 11 (resonance at both f_1 and f_2). The frequency span between f_2 and f_1 can be easily controlled, thereby reducing the required spectrum. In other words, every resonator of the proposed tag can encode two bits. The proposed technique allows the storage of a large amount of data in a compact size to reduce the cost per bit. The prototype consisted of six microstrip resonators designed and fabricated on the RT Duroid 5880 substrate ($\epsilon_r = 2.2$, $\tan \sigma = 0.0009$, and $h = 0.79$ mm). The information of each resonator can be stored in two frequencies f_1 and f_2 . The implemented tag

prototype can be reconfigured for 4^6 codes and 12 possible frequencies. The prototype was fabricated and the results were validated. The measured results were found to be in good agreement with the simulations. The remainder of this paper is organized as follows. Section 2 discusses the basic operation of the proposed resonator. The analysis and design of the six resonators of the suggested structure are explained in Section 3. Three different codes are also designed and experimentally validated. The design and testing of a complete RFID tag based on the proposed structure are discussed in Section 4. Finally, conclusions are drawn in Section 5.

Figure 2. Coupled resonator (a) geometry and (b) equivalent circuit.

2. Two-Bit Coupled-Line Stopband Resonator

The schematic diagram and equivalent circuit of the proposed coupled-line resonator are shown in Figure 2. This coupled-line resonator can be analyzed in the manner suggested by Jones and Bolljahn [35]. The stopband characteristics of this resonator can be explained in terms of image impedances Z_{I1} and Z_{I2} .

The image impedances of the coupled line shown in Figure 2 at ports 1 and 2 are given by the following:

$$Z_{I1} = \frac{2Z_{oe}Z_{oo} \cos \theta}{\sqrt{-(Z_{oe} - Z_{oo})^2 + (Z_{oe} + Z_{oo})^2 \cos^2 \theta}} \quad (1)$$

$$Z_{I2} = \frac{Z_{oe}Z_{oo}}{Z_{I1}} \quad (2)$$

where θ is the coupled line electrical length, and Z_{oe} and Z_{oo} are the characteristic impedances of the even and odd mode, respectively. These equations show that the fundamental stopband resonance occurs when $\theta = \pi/2$, that is, when the coupled line length is equal to one quarter-wavelength at the fundamental resonance frequency f_0 . This structure also produces stopband characteristics at all odd harmonics.

For the purpose of compactness, or any other appropriate layout arrangements, the quarter-wavelength line can be bent (as shown in Figure 3) without losing the stopband behavior, apart from a slight shift in the resonance frequency. If the electrical length of the coupled line section is denoted as θ_1 and the electrical length of the vertical line is θ_2 , then the total electric length is $\theta = \theta_1 + \theta_2$. At the fundamental resonance frequency, very little decrease in the total electrical length is noticed. As an example, θ changes from 90° to 85° when θ_1 decreases from 90° to 30° . However, the bandwidth of the resonator decreases as θ_1 decreases.

Figure 3. Coupled bent resonator.

For cost-effective chipless RFID, the short circuit is usually replaced by an open-circuit quarter-wavelength stub at f_0 . In this case, the fundamental resonance frequency remains unchanged at f_0 . However, the first harmonic appears at approximately $2f_0$.

In our design, the short circuit in Figure 3 can be replaced by a quarter-wavelength open-circuit stub at f_1 or f_2 , where f_1 and f_2 are close to each other. For a proof of concept, the proposed resonator shown in Figure 4 is designed to have f_1 and f_2 at 5 and 5.2 GHz, respectively. The circuit was designed on the Duroid substrate of a dielectric constant 2.2 and thickness 0.78 mm. The physical parameters of the circuit shown in Figure 4 are given in Table 1. This coupled line of length l_c and width w_c can be connected to arm 1, arm 2, or both arms using short metallic strips through a vertical arm of length l_v and width w_v . This resonator can be reconfigured in order to present a quad-state.

Figure 4. Geometry of the proposed resonator.

Table 1. Physical parameters of single coupled-line resonator.

Parameter	w_f	gap	l_c	w_c	l_v	w_v	S_1	S_2
Value (mm)	2.4	0.2	9.55	0.5	3.8	0.5	2	1.3

The various types of states can be obtained using the connections shown in Figure 5. The first state, S_1 -state, is achieved when arms 1 and 2 are not connected to the vertical line. No resonance can be observed in the band of operation, and this case is represented by the code 00. If only arm 2 is connected to the vertical line by a short metallic strip, the resonator resonance frequency in this case is f_2 and the resonator is represented by the code 01 as shown in Figure 5b (S_2 -state). The third case, S_3 -state, is when only arm 1 is connected to the vertical line by a short metallic strip. The resonance frequency is f_1 and this state is represented by the code 10. In the fourth state, S_4 -state, both arms are connected to the vertical coupled line. Therefore, the resonance occurs at f_1 and f_2 and the resonator is represented by the code 11. These four possible states are summarized in Table 2.

Figure 5. Four possible states for the single proposed resonator: (a) S_1 (no frequency), (b) S_2 (f_2 only), (c) S_3 (f_1 only), and (d) S_4 (f_1 and f_2).

Table 2. Possible states for single resonator.

Possible States	Arm 1	Arm 2	f_r	Binary Code
1st state (S_1)	Not connected	Not connected	0	00
2nd state (S_2)	Not connected	Connected	f_2	01
3rd state (S_3)	Connected	Not connected	f_1	10
4th state (S_4)	Connected	Connected	$f_1 f_2$	11

Figure 6 shows the simulated insertion and return losses of a single quad-state microstrip resonator in four possible states “00,” “01,” “10,” and “11.” From this graph, there are two distinct resonant dip nulls in the magnitude of S_{21} (f_1 and f_2). Additionally, there are two peaks in the magnitude of S_{11} , which can be also used to identify the null location. The existence of a null in the insertion loss represents logic “1,” whereas the absence of the null represents logic “0.”

Figure 6. S_{21} (a) and S_{11} (b) responses for the single quad-state microstrip resonator.

3. Multi-Resonator Structure Design and Analysis

A six-resonator circuit based on the proposed resonator discussed in the previous section was developed on the Duroid substrate of a dielectric constant 2.2 and thickness 0.78 mm. The CST Microwave Studio was used to design and simulate the proposed tag. This structure was designed to maintain the frequency span for each resonator at approximately 200 MHz. The frequency span between each two adjacent resonators was also chosen to be approximately 200 MHz. The structure layout is shown in Figure 7. For the operation from 5.4 to 8 GHz, the resonator lengths were selected from $L_1 = 9.4$ mm to $L_6 = 5.5$ mm. The separation between the adjacent resonators was 1 mm. The feeder width was designed for a characteristic impedance of 50Ω , which resulted in a width of 2.4 mm for the chosen substrate. The total length and width of the structure was 29.4 and 12.6 mm, respectively.

Figure 7. Six quad-state resonators.

Four configurations were developed to validate the concept. The first structure is shown in Figure 7, where all the resonators are connected to represent the code 11 for each one. Therefore, the configuration code is 1111111111. The second configuration represents all zeros, where the two arms of all resonators are not connected. The third configuration represents code 1010101010, and obtained with arms 1 of all the resonators connected and arms 2 not connected. The fourth configuration represents 0101010101, and consists of arms 2 of all the resonators connected and arms 1 not connected. The simulation results of S_{21} and S_{11} of the first two codes are shown in Figure 8. The simulation results of the first, third, and fourth codes are shown in Figure 9. It must be noted from this figure that almost no frequency shift was noticed when switching any resonator from one code to another. Many other codes, not presented in this paper, such as 011110011110, 110011001100, and 001100110011, were designed and verified.

Figure 8. Simulated response of the proposed resonator tag with two different IDs: 111111111111 and 000000000000; (a) S_{21} and (b) S_{11} .

Figure 9. Simulated results of the proposed tag with three different codes: 111111111111, 101010101010, and 010101010101; (a) S_{21} and (b) S_{11} .

The three codes 111111111111, 101010101010, and 010101010101 were implemented and their photographs are shown in Figure 10. The measured and simulated S_{21} were compared as shown in Figures 11–13. Only very small shifts to higher frequency were noticed in the measurements.

Figure 10. Fabricated codes: (a) 111111111111, (b) 101010101010, and (c) 010101010101.

Figure 11. Measured and simulated S_{21} for code (111111111111).

Figure 12. Measured and simulated S_{21} for code 101010101010.

Figure 13. Measured and simulated S_{21} for code 010101010101.

This may be attributed to the fabrication accuracy or high tolerance in the substrate parameters. The measurements were performed on an Anritsu Vector Network Analyzer (VNA 37369C), and showed good agreement with the simulations.

4. Integrated Chipless RFID Tag Prototype

Two typical wideband monopole antennas covering the frequency range from 5 to 10 GHz were designed and optimized to verify the proposed tag experimentally. The antenna is shown in Figure 14, and its parameters are listed in Table 3. Figure 15a shows the simulated and measured return loss. The measured bandwidth for $S_{11} < -10$ dB was extended from GHz to 12 GHz. In addition, the 3D radiation pattern at 7 GHz is displayed in Figure 15b.

Figure 14. UWB antenna (a) geometry and (b) fabricated circuit.

Table 3. UWB antenna design parameters.

Parameter	Value (mm)	Parameter	Value (mm)
Patch length (L_p)	39.6	Ground length (L_g)	34.5
Patch width (W_p)	25	Ground width (W_g)	25
Gap between the patch and ground plane (gap)	0.52	Feeder length (L_f)	35
		Feeder width (W_f)	2.4

Figure 15. UWB antenna results (a) simulated and measured S_{11} (b) simulated 3D radiation pattern.

The two antennas were connected to opposite ends of the feeder line of the six-resonator structures implemented in the previous section. The two antennas were placed in an orthogonal-polarization arrangement, as shown in Figure 16.

Figure 16. Integrated chipless RFID tag prototype.

A measurement setup was established to validate the proposed chipless RFID tag system, as shown in Figure 17. The test was performed in an anechoic chamber, and two different six-resonator tag codes were used. Tag (1) had code 11111111111, and tag (2) was 101010101010. The measured results of tag (1) and tag (2) are illustrated in Figures 18 and 19, respectively. It can be seen from these figures that the measured and simulated results matched well, with slight shifts in certain resonance frequencies.

Figure 17. Measurement setup.

Figure 18. Measured and simulated S_{21} of code 111111111111.

Figure 19. Measured and simulated S_{21} of code 101010101010.

5. Conclusions

In this study, a novel and compact chipless RFID tag was designed and fabricated. This structure contains six quad-state microstrip coupled-line resonators. For each resonator, two resonance frequencies are possible; therefore, a single resonator can be reconfigured for two-bit information codes (00, 01, 10, and 11), which is more economical than conventional chipless RFID tag designs. The proposed tag can be reconfigured for 4^6 codes and 12 possible frequencies. The measured insertion loss is found to be in good agreement with the simulation.

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