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Hybrid model chipless RFID tags based on the integration of filter theory and multi-resonator circuit

Filtre teorisi ve çoklu rezonatör devresinin entegrasyonu temeline dayalı hibrit model çipsiz RFID etiketleri

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Abstract

In this paper, a hybrid model chipless radio frequency identification (RFID) tag is introduced. It is constructed by using multi-resonator circuit with a bandstop filter simultaneously. Bandstop filter section is conventionally designed by quarter-wave open-circuited stubs, while the multi-resonator circuit is developed by coupling dual-band co-directional split ring resonators (CDSRRs) to a feeding line. Each stub and CDSRR can provide two and four frequency codes, respectively. The open-circuited stubs can form the resonant frequencies within wide frequency range, while the CDSRRs have notch band characteristics. The proposed hybrid model approach has the ability of combining notch and wide band resonant frequencies on a single circuit. A 12-bit chipless RFID tag is designed by locating two wideband monopole antennas vertically and horizontally at the end of the multi-resonator circuit. The monopole antennas are formed by using two orthogonal ellipses. 000000000000 and 100100100100 frequency coded two tags have been experimentally investigated.

Keywords: Chipless, RFID tag, Split ring resonator, Bandstop filter, Monopole antenna.

Öz

Bu makalede, bir hibrit model çipsiz radyo frekansı tanımlama (RFID) etiketi tanıtılmaktadır. Bu etiket çoklu rezonatör devresinin bir bant durduran filtre ile eş zamanlı kullanılmasıyla oluşturulmaktadır. Çoklu rezonatör devresi çift bantlı eş yönlü ayrık halka rezonatörlerin (CDSRR) bir besleme hattına kuplajlanmasıyla geliştirilirken, bant durduran filtre bölümü çeyrek dalga boyunda açık devre sonlandırmalı saplamalar kullanarak tasarlanmaktadır. Her yan hat ve CDSRR, sırasıyla iki ve dört frekans kodu sağlayabilmektedir. CDSRRlar çentik bant karakteristiğine sahipken, açık devre saplamalar rezonans frekanslarını geniş frekans aralığında oluşturabilmektedir. Önerilen hibrit model yaklaşımı, çentik ve geniş bant rezonans frekanslarını tek bir devre üzerinde birleştirme yeteneğine sahiptir. 12 bitlik çipsiz bir RFID etiketi, çoklu rezonatör devresinin ucuna dikey ve yatay olarak iki geniş bant monopol anten yerleştirilerek tasarlanmaktadır. Monopol antenler iki ortogonal elips kullanılarak oluşturulmaktadır. 000000000000 ve 100100100100 frekans kodlarına sahip iki etiket deneysel olarak incelenmiştir.

Anahtar kelimeler: Çipsiz, RFID etiketi, Ayrık halka rezonatör, Bant durduran filtre, Monopol anten.

1 Introduction

[2]Depending on the advancement in item tracking technologies, importance of radio frequency identification (RFID) systems gradually increases. A conventional RFID system consists of a reader, reader antenna, RFID tag and a host computer. Such systems can identify and track items without line of sight and at hard environment conditions. They can also allow longer reading distance as compared to barcodes. Item tracking process can be achieved by chipped or chipless RFID tags having different identification numbers assigned to different objects. Chipless RFID tags have remarkable advantages as compared to the chipped tags since they are low cost.

Until now, many chipless RFID tags have been carried out according to their frequency or time domain coding methods [1]. Among these, spectral signature based chipless RFID tags stand out since they can allow flexible design methodologies and production in a cost-effective way. In recent years, filter theory approach and multi-resonator circuits are very popular in chipless RFID tag design. Bandstop filter design approach is generally used for filter theory based chipless RFID tags. In [2]-[6], bit resonances can be obtained by quarter-wave open stubs and tapered microstrip lines are required for impedance matching. The bit resonances are occurred within a high bandwidth, so that it is getting harder to reach very high data storage capacity. Filter theory based chipless RFID tags have also been designed with first- and second-order resonance characteristics [7]. Although efficient performance can be performed, the tag suffers from the large circuit size. In addition, very thin stub widths are needed to achieve high data storage capacity. On the other hand, chipless RFID tags having multi-resonator circuits keep their popularity, since they can allow much more resonant frequencies as compared to the tags based on bandstop filters. Spiral resonator structures can provide two frequency codes (states) and they are most popular topology in multi-bit chipless RFID tag design [8]-[14]. In [9], 35 open loop resonators have been used to achieve 35 resonant frequencies. In recent years, it is desired to obtain more than 2 bits from one resonator for size reduction. For this

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purpose, stub loaded or open/closed loop dual-mode resonators are introduced to satisfy three states [15],[16]. Moreover, complimentary split ring resonators and stub loaded dual-mode resonators with different coupling topologies have been developed to obtain multiple states from a single resonator in [17]-[20]. In the chipless RFID tags based on multi-resonator circuits, data storage capacity can be obtained by adding more resonators, so that the overall size is increased. Therefore, a hybrid model that combines multi-resonator circuits and filter design techniques can be a milestone in the literature of chipless RFID tags. To the best of our knowledge, an RFID tag consisted of multiple resonators and open stubs has not been introduced to the literature.

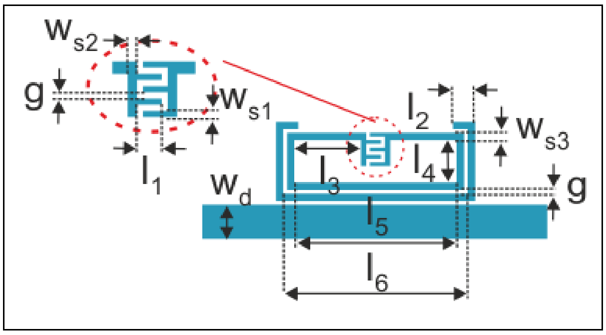
In this paper, a novel chipless RFID tag model is presented by using multi-mode resonators and open-circuited stubs simultaneously. The open-circuited stubs are about quarter wavelength and each stub can create one resonant frequency. Hence, 2^N frequency codes can be produced by using N stubs. Moreover, co-directional split ring resonators (CDSRRs) are coupled to the feeding line to increase the frequency code variation. As described in [21] and [22], two resonant frequencies can be obtained from a CDSRR. Four different states can also be achieved with respect to the suitable lengths of the inner and outer open loop resonators of the CDSRR. A 12-bit chipless RFID tag is designed by using two elliptic shaped monopole antennas in vertical/horizontal polarizations. The proposed hybrid model approach can allow obtaining more bits than the filter theory based tags within the same frequency range. The frequency range of the designed tag is between 2.4 and 5.88 GHz. Two tags having different identification codes have been successfully measured. The proposed approach combines the advantages of multi-resonator circuits and filter design techniques in a single chipless RFID tag.

2 Frequency coding process

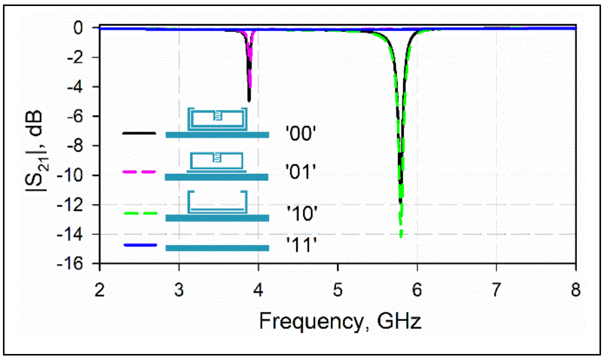
For the spectral signature based chipless RFID tags, an identity is assigned to the tag depending on its resonant frequencies produced by the multi-resonator circuit. The multi-resonator circuit actually behaves like a bandstop filter, so that the identity of the tag can be determined from the insertion loss of the two port multi-resonator circuit. Hence, if there is a transmission zero at any frequency, it represents the bit of logical '0', otherwise the bit will be the logical '1'. In all design steps and experimental studies, Rogers 5870 substrate with a dielectric constant of 2.33 and a thickness of 0.508 mm has been used.

2.1 Co-directional split ring resonators

CDSRRs can be formed by nested open loop resonators with interdigital capacitors located between the open ends of the inner resonator. They can exhibit two resonant frequencies due to the existence of the interdigital capacitor as theoretically explained in [21]. Accordingly, four frequency codes can also be achieved from a CDSRR by eliminating the resonant frequencies independently. Hence, 4^N frequency codes can be obtained by using N CDSRRs. For the design procedure, two bits (resonant frequencies) should be firstly obtained from a CDSRR. A CDSRR coupled to the feeding line is illustrated in Figure 1(a), where input and output ports are used instead of the antennas to investigate the bit characteristics of the CDSRR. Frequency codes of 00 and 11 are obtained by using the CDSRR or removing, respectively. For the frequency code of 01, the lateral arms of the outer open loop resonator must be removed. This means that the outer open loop resonator consists of only the coupled section. In this case, electrical length of each uncoupled arms of the inner open loop resonator should be about $\lambda0/8$, where $\lambda0$ is the wavelength at the resonant frequency. The last frequency code 10 can be created by removing the lateral and upper arms of the inner open loop resonator. Here, the electrical length of the uncoupled arm of the outer open loop resonator should be again about $\lambda0/8$. It is clear that the frequency codes of 01 and 10 can be achieved by converting the CDSRR to an open loop resonator having a coupled section. Four frequency codes obtained from a CDSRR are depicted in Figure 1(b). As can be seen from the figure, both of the resonant frequencies at all frequency codes exhibit notch band characteristics. Related configurations for all frequency codes are also demonstrated in the inset of Figure 1(b).



(a)



(b)

Figure 1(a): Layout of a CDSRR coupled to a straight feeding line (l_1= 0.8, l_2=1.2, l_3= 3.6, l_4= 2.3, l_5 = 8.8, l_6= 10, W_{s1}= W_{s2}= 0.2, W_{s3}= 0.4, W_d= 1.5, g= 0.2, all dimensions in mm), (b): frequency responses.

2.2 Bandstop filter having open-circuited stubs

As is well known, a bandstop filter can be designed by using open-circuited shunt stubs as described in [23]. Such kind of bandstop filters can be used to design chipless RFID tags [2]. In a similar manner, open-circuited stubs at quarter wavelength may result two states depending on its presence or absence. In other words, N open stubs can satisfy $2N$ identification codes. Frequency responses for different identification codes are demonstrated in Figure 2, where the inset figure shows the filter configuration. Here, each resonant frequency can be cancelled by removing the related stub. It should also be noted that the resonant frequencies occur within a wider frequency band as compared to Figure 1(b).

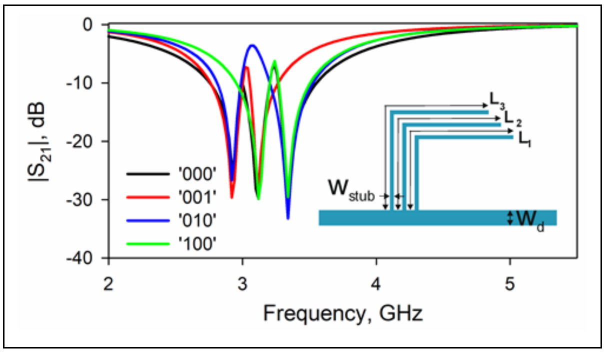


Figure 2. Frequency responses for different states of the open-circuited stub loaded bandstop filter (W_d= 1.5, W_{stub}= 0.2, L_1= 16.9, L_2= 18.1, L_3= 19.3, all dimensions in mm). Inset figure: Filter configuration.

3 Hybrid model chipless RFID tag

3.1 Construction of multi-resonant circuit

The designed multi-resonant circuit of the chipless RFID tag is based on the utilization of CDSRRs and open-circuited stubs on the same circuit as illustrated in Figure 3.

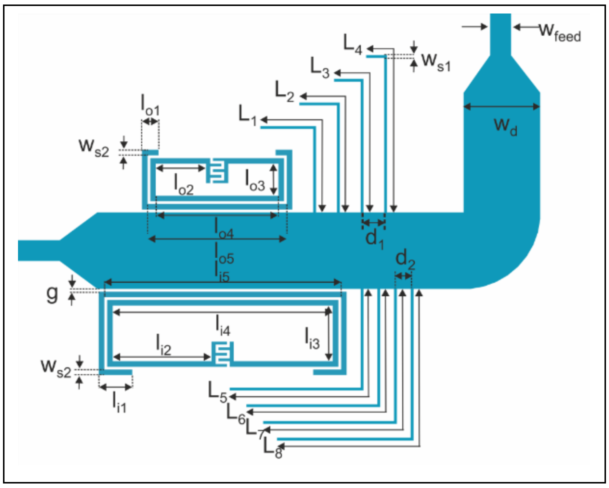


Figure 3. Layout of the proposed multi-resonant circuit having CDSRRs and open stubs (l_{o1}= 1.2, l_{o2}= 3.6, l_{o3}= 2.3, l_{o4}= 8.8, l_{o5}= 10, l_{i1}= 2.4, l_{i2}= 7.1, l_{i3}= 4, l_{i4}= 15.8, l_{i5}= 17, W_{s1}= 0.2, W_{s2}= 0.4, W_{feed}= 1.5, W_d= 5.5, W_{gap}= 0.2, d_1= 1.5, d_2= 1, L_1= 10.2, L_2= 10.8, L_3= 11.7, L_4= 12.8, L_5= 16.9, L_6= 18.1, L_7= 19.3, L_8= 20.7. (All dimensions in mm).

The proposed multi-resonant tag can produce totally 2^{2Nr+Ns} frequency codes, where Nr and Ns are the numbers of the CDSRRs and open stubs, respectively. For this purpose, physical lengths of the CDSRRs should be firstly determined for the desired frequencies. Then, the designed CDSRRs are coupled to the feeding line that connects the receiving and transmitting antennas. It should be noted that the feeding line is tapered to minimize the effects of impedance mismatch. The CDSRRs should be located at the upper and bottom sides of the feeding line to achieve the compactness. The quarter wavelength open stubs are connected to the feeding line after the CDSRRs. In Fig. 3, two CDSRRs and eight open stubs are used to obtain totally twelve resonant frequencies within the frequency range of 2.4 and 5.4 GHz. The resonant frequencies of the CDSRRs are adjusted to 2.4, 3.54, 3.88 and 5.82 GHz, while they are at 2.66, 2.88, 3.08, 3.32, 4.3, 4.68, 5.06 and 5.4 GHz for the open stubs. Different frequency code combinations which are obtained by means of CDSRRs and open stubs are successfully investigated in Figure 4(a), where the bit frequencies are negligibly affected from the stub or CDSRR removal process. Figures 4(b) and 4(c) represent the possible minimum frequency intervals between different resonant frequencies. Since CDSRR exhibits notch band characteristics, the minimum frequency range can be reduced up to 30 MHz as shown in Figure 4b. Here, the first resonant frequency can be resulted from the CDSRR, while the second one comes from the open stub. The similar frequency interval between the resonant frequencies of two stubs can be obtained as 120 MHz as depicted in Figure 4c. Therefore, the proposed hybrid model approach can increase number of bits in the filter theory based tags, since resonant frequencies can be observed in narrower frequency band. In brief, more bandwidth can be required if the tag is designed by using only open stubs. Furthermore, in case of using only CDSRRs, the design of chipless RFID tag operating within the same frequency range may need larger circuit area than that of the hybrid model approach.

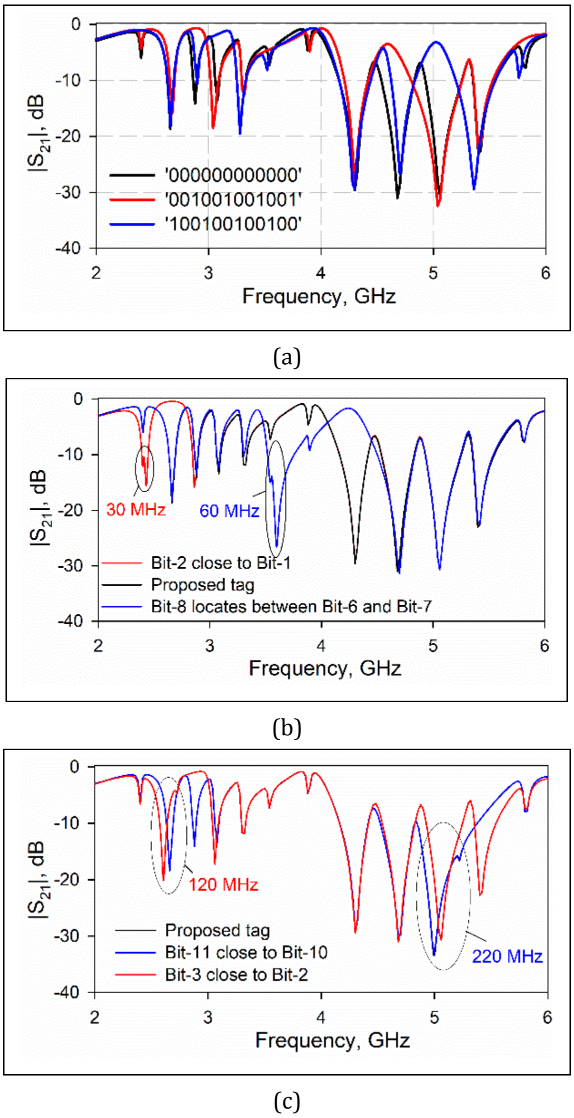
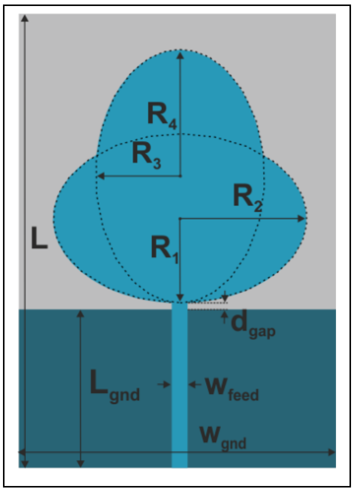


Figure 4(a): Frequency responses for different frequency codes. Minimum possible frequency intervals between the resonant frequencies of (b): the stubs and resonators. (c): Two stubs.

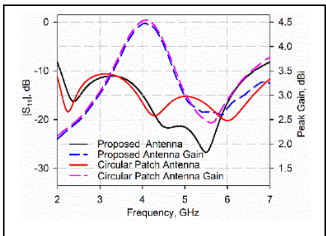
3.2 Proposed monopole antenna

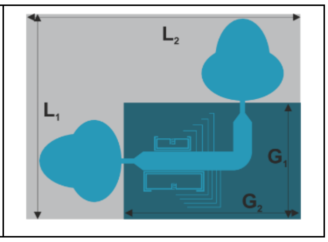
The wideband monopole antenna to be used in the chipless RFID tag is designed by combining two elliptic shaped radiating elements as depicted in Figure 5(a). Dimensions of the designed antenna are adjusted so as to operate within a frequency range of 2-6 GHz by using CST Microwave Studio 2020. Simulated return loss and peak gain varying from 2 to 4.5 dBi between 2 and 6 GHz are illustrated in Figure 5(b), where simulated responses of the circular monopole antenna are also depicted for comparison. It is obvious that the proposed can improve the return loss within a narrower band covering the tag frequencies. The return loss in Figure 5(b) is given for the comparison of the proposed elliptic shaped antenna and the conventional circular patch antenna.

The elliptic shaped monopole antennas are required for receiving the wave coming from the transmitter antenna of the reader and also transmitting it to the receiver antenna of the reader. For this purpose, they are integrated at the ends of the multi-resonant circuit instead of the input and output ports. The final layout of the proposed 12-bit chipless RFID tag is shown in Figure 5(c), where the multi-resonant circuit has same dimensions with Figure 3. It is clear that vertically/horizontally polarized monopole antennas are located. Overall size of the designed tag is 60 mm x 80 mm.



(a)





(b) (c)

Figure 5(a): Wideband monopole antenna with elliptic shaped radiating elements (L=60, L_{gnd}=31, W_{gnd}=34, W_{feed}=1.5, R_1=8, R_2=12, R_3= 8, R_4=12, d_{gap}=0.6). (b): Simulated reflection coefficients and peak gains of the proposed and circular patch antennas (Solid lines: $|S_{11}|$, dashed lines: peak gain).
(c): proposed hybrid model chipless RFID tag (L_1=60, L_2=80, G_1= 34.1 G_2= 51.7) (All dimensions in mm).

4 Experimental studies

In order to verify the simulated results of the introduced For the validation of the simulated results for the designed tag, two circuits with and without CDSRRs were fabricated and tested. Measurements of the fabricated tags were performed by using a Vector Network Analyzer of Keysight PNA N5222A in a hand-made anechoic chamber. Two RF Spin-DRH20E horn antennas have been used as receiver and transmitter in the test environment as shown in Figure 6. Here, the Network Analyzer was used as reader and both of the horn antennas can be used as receiver or transmitter of the reader. The most important point here is that the transmitter antenna of the tag must be in same polarization with the receiver antenna of the reader. The same is also valid for the receiver of the tag and the transmitter of the reader. The distance between the chipless RFID tag and the transmitter and receiver antennas of the Network Analyzer was set about 6 cm.

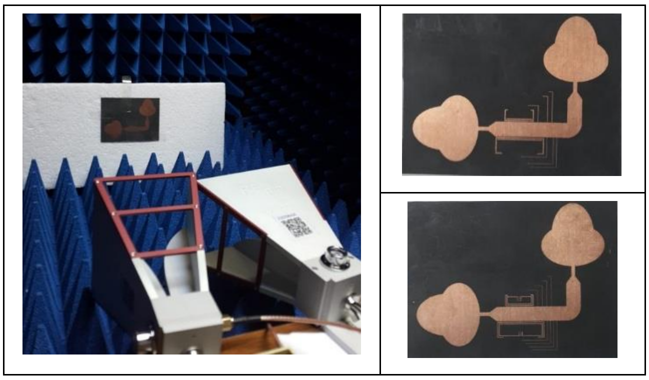
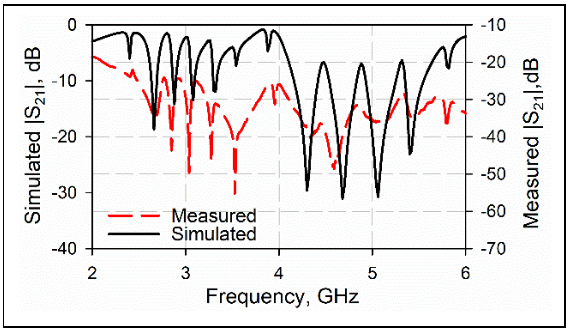
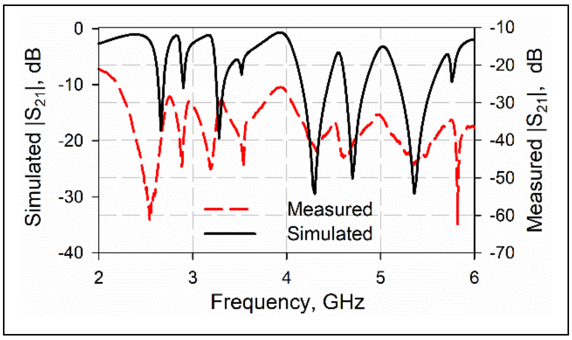


Figure 6. Photograph of the measurement environment and tags.

The measured and simulated results are compared in Figures 7(a) and 7(b). The tags were measured under same conditions by changing only the tag. Figure 7(a) represents the results of the tag with the frequency code of '000000000000'. It is clear that all the bits can be observed in the measured results. The measured bit frequencies are at 2.4, 2.66, 2.88, 3.08, 3.32, 3.54, 3.88, 4.3, 4.68, 5.06, 5.4 and 5.82 GHz. Measured and simulated results for the tag with the frequency code of '100100100100' are also shown in Figure 7(b). Here, the measured bit frequencies are at 2.66, 2.9, 3.28, 3.52, 4.3, 4.7, 5.36 and 5.76 GHz. The simulated results are two-port lossy circuit results without monopole antennas, while the measured results include the environmental conditions such as polarization crosstalk, position of horn antennas, and antenna gains. Therefore, magnitudes of S_{21} are different in the measured and simulated results. However, the most important point is the location of the resonant frequencies (dips) for the proposed chipless RFID tags. It is clear that all resonant frequencies can appear in both of the simulated and measured results in a good agreement. Frequency shifts in some resonant frequencies are due to the fabrication errors. Furthermore, magnitudes of S_{21} can be improved by using different monopole antennas having better gain performance. It is expected that the proposed hybrid model approach based multi-resonant circuits can be used in different chipless RFID tags or systems by means of the integration of different antennas.



(a)



(b)

Figure 7. Comparisons of the simulated and measured results for the frequency codes of (a): 000000000000. (b): 100100100100.

Although the filter theory based tags exhibit remarkable rejection levels, they cannot provide much more bits as the multi-resonator circuits due to their high bandwidth requirement. High data storage capacity can be achieved by using multi-resonator circuits which exhibit notch band characteristics at the resonant frequencies. However, in this case, the circuit size may increase depending on the resonator type. Therefore, the proposed hybrid model approach can combine the advantages of filter theory and multi-resonator circuits on a single circuit. The proposed approach introduces an efficient and advantageous way to increase the data storage capacity of filter theory based tags. In addition, the CDSRRs exhibiting four states are firstly utilized in chipless RFID tags. Although a 12-bit example is introduced here, number of bits can be increased by adding more resonators and stubs.

5 Conclusion

A novel hybrid model multi-resonant circuit for chipless RFID tags has been designed by using CDSRRs and open stubs. By means of the proposed approach, it is possible to get closer bit frequencies come from stubs and multi resonator circuits with suitable rejection levels. A monopole antenna constructed by two ellipses has also been introduced and integrated to the multi-resonant circuit to create the complete chipless RFID tag. To demonstrate the proposed method, two tags with different identification codes have been manufactured and successfully tested. The CDSRRs can exhibit notch band characteristics, while the open stubs need wider frequency range for the resonant frequencies. Therefore, the proposed hybrid model multi-resonant circuits can combine the advantages of multi-resonator and filter theory based tags. As a future work, it may be suggested that less than 12 bits can be achieved within a narrower frequency band, where the antenna gain is high. More than 12 bits can also be achieved within the same frequency band as that of this paper by using more stubs, CDSRRs, or different resonator types. Moreover, performance of the proposed chipless RFID tags can be improved by using new monopole antennas having higher or more linear gain.

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7 References

[1] Preradovic S, Karmakar NC. "Chipless RFID: Bar code of the future". *IEEE Microwave Magazine*, 11(7), 87-97, 2010.

[2] Nijas CM, Dinesh R, Deepak U, Rasheed A, Mridula S, Vasudevan K, Mohanan P. "Chipless RFID tag using multiple microstrip open stub resonators". *IEEE Transactions on Antennas and Propagation*, 60(9), 4429-4432, 2012.

[3] Ashraf MA, Alshoudokhi YA, Behairy HM, Alshareef MR, Alshebeili SA, Issa K, Fathallah H. "Design and analysis of multi-resonators loaded broadband antipodal tapered slot antenna for chipless RFID applications". *IEEE Access*, 5, 25798-25807, 2017.

[4] Mousa ME, Abdullah HH, El din Abo El-Soud M. "Compact chipless RFID tag based on fractal antennas and multiple microstrip open stub resonators". *2018 Progress in Electromagnetics Research Symposium (PIERS-Toyama)*, 01-04 August, 2018.

[5] Prabavathi P, Rani SS. "Design of frequency-signature based multiresonators using quarter wavelength open ended stub for chipless RFID Tag". *2019 National Conference on Communications (NCC)*, 20-23 February, 2019.

[6] Nijas CM, Vinesh PV, Sajitha VR, Anila PV, Mohanan P. "Optimisation of quarter wave microstrip open stub resonators for chipless RFID applications". *2013 IEEE Antennas and Propagation Society International Symposium (APSURSI)*, 07-13 July, 2013.

[7] Zhang YJ, Gao RX, He Y, Tong MS. "Effective design of microstrip-line chipless rfid tags based on filter theory". *IEEE Transactions on Antennas and Propagation*, 67(3), 1428-1436, 2019.

[8] Tu MT, Cheong P, Choi WW. "Defected ground structure with half-wavelength spiral resonator of ultrawide band chipless RFID tag". *IEEE Journal of Radio Frequency Identification*, 3(3), 121-126, 2019.

[9] Preradovic S, Balbin I, Karmakar NC, Swiegers GF. "Multiresonator-Based chipless RFID system for low-cost item tracking". *IEEE Transactions on Microwave Theory and Techniques*, 57(5), 1411-1419, 2009.

[10] Lopes B, Ferreira T, Matos JN. "Design guidelines for gap coupled spiral microstrip resonators in chipless RFID Tags". *IEEE Journal of Radio Frequency Identification*, 4(4), 525-531, 2020.

[11] Rodrigues RAA, Gurjão EC, de Assis FM. "Radar cross-section and electric field analysis of backscattering elements of chipless RFID tag". *2014 IEEE RFID Technology and Applications Conference (RFID-TA)*, 08-09 September, 2014.

[12] Pranonsatit S, Narkcharoen P. "Chipless RFID multiresonators fabricated by Fill until Full (FuF) technique". *2012 IEEE International Conference on RFID-Technologies and Applications (RFID-TA)*, 05-07 November, 2012.

[13] Koswatta RV, Karmakar NC. "A novel reader architecture based on UWB chirp signal interrogation for multiresonator-based chipless RFID tag reading". *IEEE Transactions on Microwave Theory and Techniques*, 60(9), 2925-2933, 2012.

[14] Sharma V, Hashmi M. "Chipless RFID tag based on open-loop resonator''. *2017 IEEE Asia Pacific Microwave Conference (APMC)*, 13-16 November, 2017.

[15] Girbau D, Lorenzo J, Lazaro A, Ferrater C, Villarino R. "Frequency-Coded chipless RFID tag based on dual-band resonators". *IEEE Antennas and Wireless Propagation Letters*, 11, 126-128, 2012.

[16] Gorur AK, Dogan E, Ayas G, Karpuz C, Gorur A. "Multibit Chipless RFID Tags Based on the Transition Among Closed- and Open-Loop Resonators". *IEEE Transactions on Microwave Theory and Techniques*, 70(1), 101-111, 2022.

[17] Bhuiyan MS, Azad A, Karmakar N. "Dual-band modified complementary split ring resonator (MCSRR) based multi-resonator circuit for chipless RFID tag". *2013 IEEE Eighth International Conference on Intelligent Sensors, Sensor Networks and Information Processing*, 02-05 April, 2013.

[18] Athauda T, Karmakar NC. "The Realization of chipless RFID resonator for multiple physical parameter sensing". *IEEE Internet of Things Journal*, 6(3), 5387-5396, 2019.

[19] Abdulkawi WM, Sheta AFA. "Four-state coupled-line resonator for chipless RFID tags application". *Electronics*, 8(5), 1-12, 2019.

[20] Abdulkawi WM, Sheta AA. "K-state resonators for high-coding-capacity chipless RFID applications". *IEEE Access*, 7, 185868-185878, 2019.

[21] Gorur AK. "A Dual-Band Balun BPF using codirectional split ring resonators". *IEEE Microwave and Wireless Components Letters*, 30(10), 949-952, 2020.

[22] Gorur AK. "A novel dual-band bandpass filter using co-directional split ring resonators with closely spaced passbands and wide upper stopband". *International Journal of RF and Microwave Computer-Aided Engineering,* 28(4), 1-7, 2018.

[23] Pozar DM. *Microwave Engineering*. 3rd Ed. New York, USA, Wiley, 2003.