

High data density and capacity in chipless radiofrequency identification (chipless-RFID) tags based on double-chains of S-shaped split ring resonators (S-SRRs)

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Abstract. The data density per surface (DPS) is a figure of merit in chipless radiofrequency identification (chipless-RFID) tags. In this paper, it is demonstrated that chipless-RFID tags with high DPS can be implemented by using double-chains of S-shaped split ring resonators (S-SRRs). Tag reading is achieved by near-field coupling between the tag and the reader, a CPW transmission line fed by a harmonic signal tuned to the resonance frequency of the S-SRRs. By transversally displacing the tag over the CPW, the transmission coefficient of the line is modulated by tag motion. This effectively modulates the amplitude of the injected (carrier) signal at the output port of the line, and the identification (ID) code, determined by the presence or absence of S-SRRs at predefined and equidistant positions in the chains, is contained in the envelope function. The DPS is determined by S-SRR dimensions and by the distance between S-SRRs in the chains. However, by using two chains of S-SRRs, the number of bits per unit length that can be accommodated is very high. This chipless-RFID system is of special interest in applications where the reading distance can be sacrificed in favor of data capacity (e.g., security and authentication). Encoding of corporate documents, ballots, exams, etc., by directly printing the proposed tags on the item product to prevent counterfeiting is envisaged.

Keywords: chipless RFID / coplanar waveguide / split ring resonators / high data capacity / security applications

1 Introduction

Transmission lines loaded with split ring resonators (SRRs) and with other electrically small resonators [1–5] have been used in numerous microwave applications, including filters [6,7], enhanced bandwidth components [8], multiband components [9–12], microwave sensors [13–30] and chipless radiofrequency identification (chipless-RFID) tags [31,32], among others. Concerning chipless RFID tags, the interest in this work, transmission lines loaded with multiple resonant elements, each tuned to a different frequency, have been proposed as multi-resonant frequency domain based tags [31–44]. In such chipless-RFID systems, the interrogation signal is a multi-frequency sweeping signal covering the spectral bandwidth of the resonant elements, and the ID code is inferred from the dips present in the frequency response (retransmission based tags) [31–37] or in the radar cross section response (backscattered tags) [38–44], caused by the resonant elements. Therefore, the presence or absence of dips at predefined frequencies (each one corresponding to a different bit) is associated

with the logic state '1' or '0'. In general, the data capacity of these frequency-domain based tags is limited due to the required spectral bandwidth necessary to accommodate a large number of bits. Multi-state multi-resonator tags, where more than one bit of information is associated to each resonant element, have been proposed to increase the density of bits per frequency and per surface [36,37]. Another strategy consists of using more than one domain (hybrid tags) [45–49], e.g., encoders based on frequency position and polarization diversity [47], or encoders where frequency domain is combined with phase deviation [46].

Despite the efforts to increase the number of bits with the previous frequency-domain and hybrid chipless-RFID systems, the reported tags do not exhibit the data capacity of chipped tags. Another approach, based on time domain, was recently reported by the authors [50,51]. Within this approach, tags consist of a chain of identical resonant elements etched or printed on a dielectric substrate. The presence or absence of resonant elements at predefined and equidistant positions determines the logic state '1' or '0', and the number of bits is only limited by the area occupied by the tag, since the spectral bandwidth is virtually null in these tags. Therefore, high data capacity can be achieved

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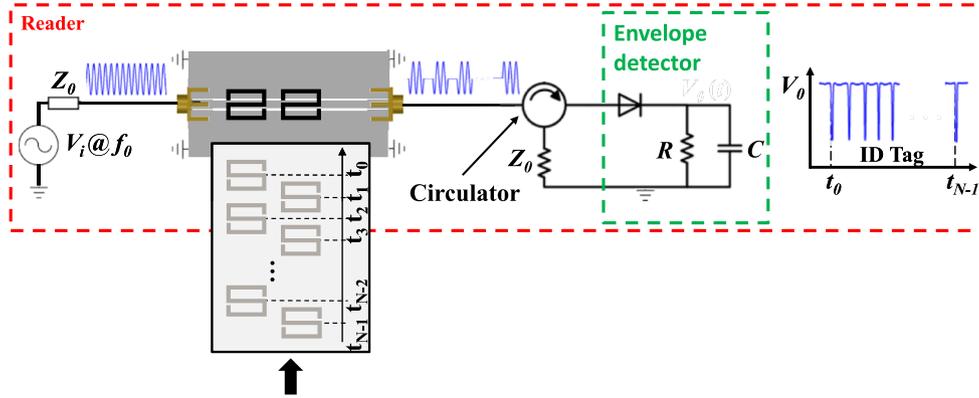


Fig. 1. Illustration showing the working principle of the proposed chipless-RFID system. A double chain of S-SRRs can be appreciated in the tag, according to the strategy to increase the data capacity per unit length proposed in the paper.

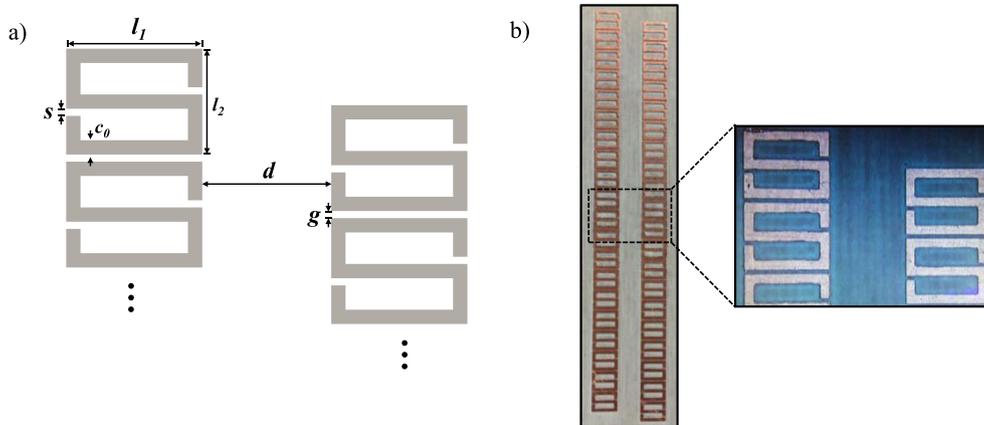


Fig. 2. Layout (zoom) of the double chain of S-SRRs (a) and photograph of the fabricated 40-bit chipless RFID tag (b). S-SRR dimensions are (in mm) $l_1 = 3.8$, $l_2 = 2.96$, $c_0 = 0.4$, $s = 0.2$, $g = 0.2$ and $d = 3.6$.

with this novel time-domain chipless-RFID systems. Nevertheless, in order to reduce the space occupied by the tags as much as possible, it is important to optimize the data density per surface (DPS), accommodating the largest possible number of resonant elements in a certain area.

In [50,51], the resonant elements are S-shaped split ring resonators S-SRRs. Tag reading proceeds sequentially through tag motion, by transversally displacing the tag over a coplanar waveguide transmission line fed by a harmonic signal tuned to the resonance frequency of the S-SRRs. By this means, the transmission coefficient of the line is modulated through near-field coupling between the line and the resonant elements. That is, each time an S-SRRs is aligned with the line axis, line-to-resonator coupling is maximized and the transmission coefficient is consequently minimized. This variable coupling, dictated by the presence or absence of resonant elements in the chain as the tag is displaced, effectively modulates the amplitude of the feeding (carrier) signal at the output port of the line, and the identification (ID) code is contained in the envelope function of the amplitude modulated (AM) signal. By using a simple envelope detector, the tag ID can thus be inferred. Figure 1 illustrates the working principle of this time-domain chipless RFID system based on near-field coupling.

In [51], 40-bit tags, occupying an area of 5.34 cm^2 and a chain length of 14 cm, were demonstrated. In this paper, we have doubled the number of bits, without significantly increasing the tag length (the critical dimension) by using a double-chain of resonant elements. The strategy to implement the double chain and the necessary modifications of the CPW transmission line (reader) are reported in this paper. The proposed system is validated by reading several fabricated tags with our experimental setup, and the ID code is obtained by visualizing the envelope function in an oscilloscope.

2 Tag and reader design and fabrication

Concerning the tags, they are based on the resonant elements used in [50,51], i.e., S-SRRs [52–54]. However, a double chain of S-SRRs is considered in this paper, with a relative displacement between S-SRR chains of half a period. The dimensions of the S-SRRs are those considered in [50,51]. A detail of the layout of the double S-SRR chain is depicted in Figure 2(a), whereas Figure 2(b) shows the picture of the 40-bit fabricated encoder with all the resonant elements present. The considered substrate for

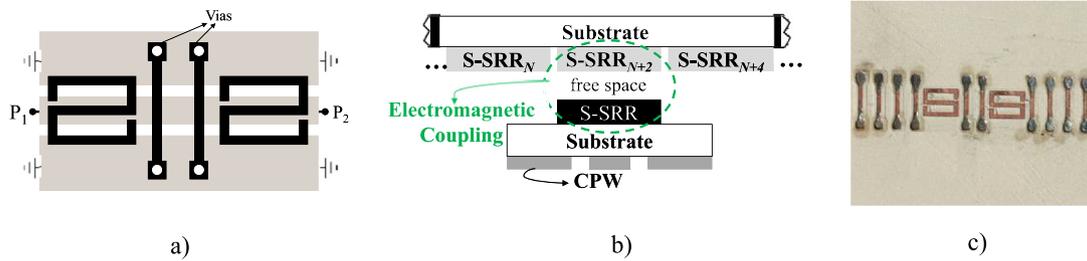


Fig. 3. Layout (a), cross sectional view including the tag (b) and photograph (c) of the designed and fabricated S-SRR-loaded CPW acting as active part of the reader. In (c) only the backside of the CPW is shown.

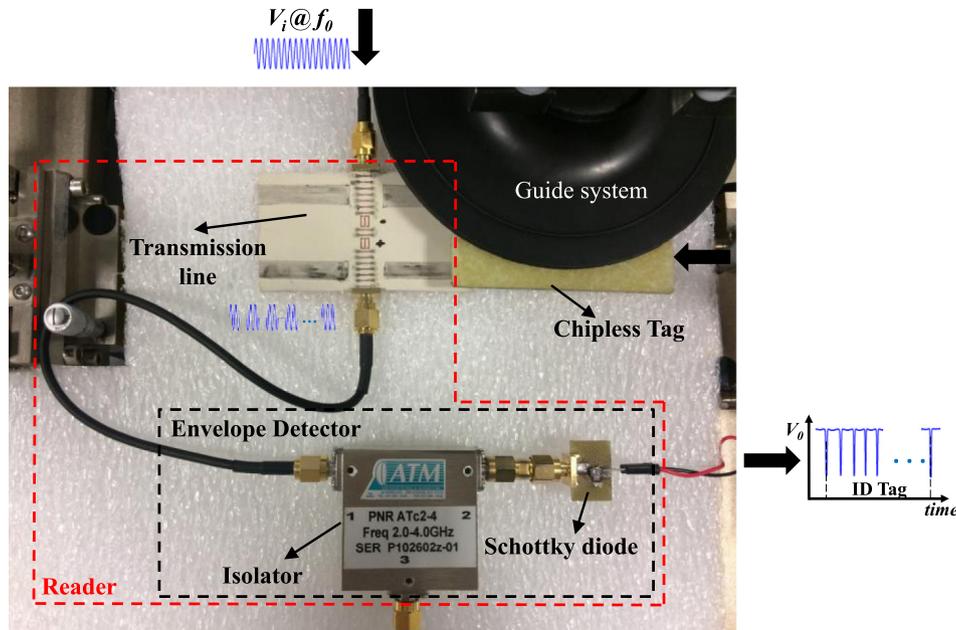


Fig. 4. Photograph of the experimental set-up.

tag implementation is the *Rogers RO4003C* with thickness $h = 203 \mu\text{m}$, dielectric constant $\epsilon_r = 3.55$ and $\tan \delta = 0.0021$.

Let us now consider the design of the CPW transmission line of the reader. In [50,51], a S-SRR identical to those of the tag was etched in the back substrate side of the CPW, a 50Ω line. The purpose of this resonant element etched in the reader side is to prevent from the appearance of inter-resonator coupling in the tag chain (through magnetoinductive waves [55–60]) as well as multiple couplings between the line and the S-SRRs of the chain [30]. The key aspect is that when one of the S-SRRs of the tag chain is perfectly aligned with the S-SRR of the reader, both particles can be viewed as a single particle, the broadside coupled S-SRR (BC-S-SRR), with smaller fundamental resonance. Thus, by tuning the frequency of the carrier feeding signal to the frequency of the BC-S-SRR, or slightly higher, the above-cited extra couplings are avoided. The reason is that the resonance frequency of the individual S-SRR is substantially higher.

If two chains of S-SRRs are considered in the tag (with a relative displacement of half a unit cell), this means that, consequently, two S-SRRs must be etched in the backside of the CPW transmission line. The distance between the S-

SRRs in the CPW must be identical to the transverse distance between the S-SRR chains. Through this approach, if a S-SRR is etched in a certain predefined position, either in the outer or inner tag chain, the corresponding ‘1’ state will be detected, since the coupling with the line is ensured. Figure 3 shows the layout, cross sectional view and photograph of the proposed and fabricated S-SRR-loaded CPW. The structure has been fabricated in the *Rogers RO3010* with thickness $h = 0.635 \text{ mm}$, dielectric constant $\epsilon_r = 10.2$.

3 Experimental set-up and validation

The photograph of the complete system is depicted in Figure 4. The frequency of the carrier signal is set to $f_c = 4 \text{ GHz}$, which is the one corresponding to the BC-S-SRR by considering an air gap of 0.25 mm . By varying the air gap distance, the resonance frequency of the BC-S-SRR, f_0 , obviously changes. If the carrier frequency is chosen as $f_c = f_0$ for a certain gap distance, and the air gap increases significantly, it may give rise to reading errors. The reason is that f_0 increases, and hence the modulation index decreases. Nevertheless, some tolerance exists since the

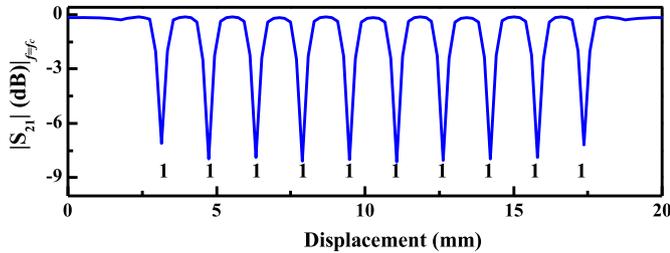


Fig. 5. Transmission coefficient at f_c , as the linear 10-bit tag is displaced above the S-SRR-loaded CPW transmission line, inferred from electromagnetic simulation using *Keysight Momentum*, by considering an air gap of 0.25 mm.

notch, centered at f_0 , exhibits certain bandwidth. Moreover, we can fine tune the carrier frequency in order to match it to the resonance frequency of the BC-SRR.

Before the experimental validation (to be discussed next), we have obtained the transmission coefficient at f_c through electromagnetic simulation, by considering a linearly shaped double S-SRR chain with all the SRRs present at the predefined positions (specifically, we have considered five S-SRRs in either chain, corresponding to a 10-bit encoder with ID code ‘1111111111’). The simulated response, obtained by displacing the tag over the S-SRR loaded CPW and depicted in **Figure 5**, reveals that the tag functionality is achieved.

In practice, the carrier signal is generated by means of the *Agilent E44338C* function generator. The output port of the S-SRR-loaded CPW is connected to an isolator (implemented with the *ATMATc4-8* circulator) in order to prevent from mismatching reflections caused by the diode, an *Avago HSMS-2860* device. Such diode is the essential part of the envelope detector, used for rectification purposes. Filtering is achieved by means of the *N2795A* active probe (with resistance $R = 1\text{ M}\Omega$ and capacitance $C = 1\text{ pF}$), connected to the *Agilent MSO-X-3104A* oscilloscope in order to visualize the envelope function providing the ID code.

Reading of three different encoders has been carried out by means of the proposed set-up. The envelope function of the 40-bit encoder with all resonators present at the predefined positions (code 1 of **Fig. 6**) has been modified to achieve codes 2 and 3 of **Figure 6**. Specifically, we have cut some resonators, making them inoperative (i.e., equivalent to their absence, or ‘0’ logic state) and hence programming the ID code corresponding to codes 2 and 3 of **Figure 6**. A drilling machine has been used to cut the required resonant elements along their symmetry plane. The data density per surface of the proposed tags is $\text{DPS} = 5.53\text{ bit/cm}^2$, and the number of bits per unit length is 5.7 bit/cm . Since tag reading proceeds sequentially, necessarily the longitudinal dimension of the proposed tags is much larger than the transverse dimension, the later being independent on the number of bits and given by the transverse size of the double S-SRR chain. Therefore, the critical aspect, provided a large number of bits is required, is the number of bits per unit length. With the resulting density of bits per unit length,

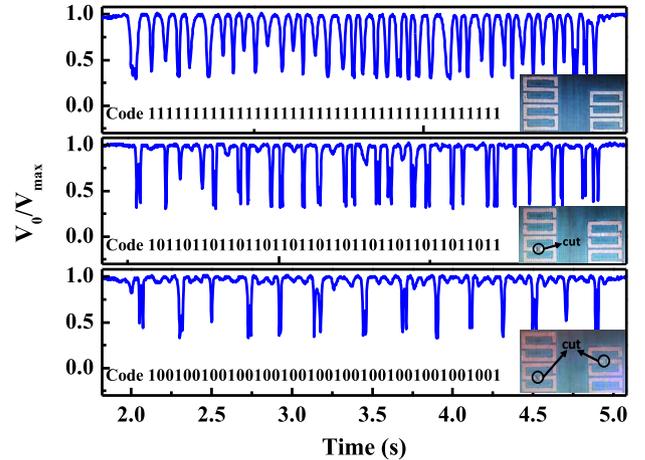


Fig. 6. Envelope functions of the 40-bit tags with the indicated codes.

it is possible to encode standard European documents (of size $29.7\text{ cm} \times 21.0\text{ cm}$) with 170 bits printed along the longer paper side.

4 Conclusions

In conclusion, a chipless-RFID system based on near-field and sequential bit reading, with tags implemented by double chains of S-SRRs, has been proposed. As compared to previous S-SRR based tags implemented with single chains of SRRs, the reported tags exhibit roughly twice the data density per unit length (i.e., 5.7 bit/cm). The strategy to accommodate such high bit density in the tags, as well as the modifications in the reader (S-SRR-loaded CPW), necessary to properly read the tags, has been discussed.

The possibility to program the tags by detuning the resonant elements has been also demonstrated, and a proof-of-concept, where the ‘0’ state has been achieved by cutting the corresponding resonant elements, has been carried out. The reported high data capacity chipless-RFID system is contactless but needs proximity between the tag and the reader. It is thus of special interest in applications where a large number of bits is necessary, and read distance can be sacrificed. Encoding of secure documents, e.g., to avoid counterfeiting, is one of the envisaged applications. Work is in progress to implement the proposed tags in plastic and paper substrates.

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