# Near-Field Chipless-RFID System with Erasable/Programmable 40-bit Tags Inkjet Printed on Paper Substrates

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***Abstract*— In this paper, a chipless radiofrequency identification (chipless-RFID) system with erasable/programmable 40-bit tags inkjet printed on paper substrates, where tag reading proceeds sequentially through near-field coupling, is presented for the first time. The tags consist of a linear chain of identical split ring resonators (SRRs) printed at predefined and equidistant positions on a paper substrate, and each resonant element provides a bit of information. Tag programming is achieved by cutting certain resonant elements, providing the logic state '0' to the corresponding bit. Conversely, tags can be erased (all bits set to '1') by short-circuiting those previously cut resonant elements through inkjet. An important feature of the proposed system is the fact that tag reading is possible either with the SRR chain faced-up or faced-down (with regard to the reader). To this end, two pairs of header bits (resonators), with different sequence, have been added at the beginning and at the end of the tag identification (ID) chain. Moreover, tag data storage capacity (number of bits) is only limited by the space occupied by the linear chain. The implementation of tags on paper substrates demonstrates the potential of the proposed chipless-RFID system in secure paper applications, where the necessary proximity between the reader and the tag, inherent to near-field reading, is not an issue.**

***Index Terms* — Chipless-RFID, microstrip, split ring resonator, secure paper.**

## I. Introduction

Chipless-RFID is a wireless technology used for identification, tracking, sensing, and authentication/security applications. In the field of authentication and security, one promising scenario for chipless-RFID is secure paper. Within this particular application, equipping documents (e.g., banknotes, certificates, exams, ballots, official documents, etc.) with a planar identification (ID) code is envisaged as a means to fight against counterfeiting. The main general advantage of chipless-RFID over chipped-RFID systems is the absence of silicon integrated circuits (IC), or chips, which are replaced with printed encoders in chipless-RFID tags. Such encoders can be fabricated by means of printing techniques, such as screen printing, rotogravure, flexography or inkjet, and represent a low-cost solution as compared to conventional chipped tags. However, chipless-RFID tags present two main limitations: (i) data capacity and (ii) tag size.

Many efforts have been carried out in recent years to partially alleviate the previous limitations of chipless-RFID systems. In frequency-domain based chipless-RFID systems [1]-[3], encoders with multiple resonant elements, each one tuned to a different frequency, are used for coding. In such systems, the ID code is given by the presence/absence of abrupt spectral characteristics in the amplitude, phase or group delay response of the tags, and each resonant element provides a bit of information. Thus, in order to increase the data density, and hence reduce tag size, hybrid techniques, where more than one domain is used simultaneously, have been reported [4]-[7]. Nevertheless, these hybrid approaches are still far from providing the data storage capability of UHF-RFID chipped tags. Moreover, the spectral bandwidth required to accommodate a significant number of bits is very high, and this is not compatible with the implementation of low-cost readers. Alternatively, in the so-called time-domain based chipless-RFID systems, the ID code is determined from the echoes generated by a set of reflectors printed on a transmission line (the interrogation signal being a narrow pulse in time domain) [8]. Within such approach, the number of bits is limited by the need to avoid overlapping between reflected pulses.

In this work, a different time-domain approach based on near-field and sequential bit reading, first reported in [9], [10], is used for reading new 40-bit chipless-RFID tags inkjet printed on paper substrates. The working principle of the proposed system is depicted Fig. 1. The tags consist of a linear chain of identical equidistant resonators, either tuned (i.e., functional, hence providing the logic state '1') or detuned ('0'). The interrogation signal is a harmonic (carrier) signal tuned to the resonance frequency of the set of resonators, and the ID code is obtained from the envelope of the amplitude modulated (AM) signal generated by tag motion. That is, tag

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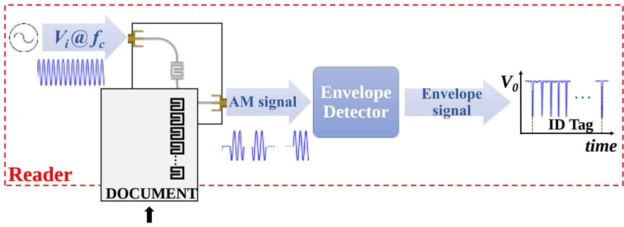


Fig. 1. Illustration of the working principle of the proposed chipless-RFID system. In a reading operation, the tag is displaced at short distance over the reader through a mechanical guiding system providing tag/reader alignment.

reading proceeds through near-field coupling, by displacing the tag over the reader, a transmission line fed by the harmonic (carrier) signal. The presence or absence of functional (tuned) resonators at the predefined positions determines the ID code of the tag, as long as signal transmission (and hence the output amplitude) is related to line-to-resonator coupling (variable with tag motion and only manifested when a tuned resonator is on top of the transmission line).

## II. Reader and Programmable/Erasable Tags

The active part of the reader is a microstrip line loaded with a split ring resonator, SRR [Fig. 2(a)], and it is implemented on the *Rogers RO3010* substrate with thickness $h$ = 1.27 mm and dielectric constant $\varepsilon_r$ = 10.2. The magnitude of the transmission coefficient ($S_{21}$) of this structure (unloaded reader) exhibits a pass band behaviour with a transmission zero, as depicted in Fig. 3. Such response shifts down when the active part of the reader is loaded with the tag (see also Fig. 3), and the displacement level depends on the coupling between the tag and the reader. Indeed, the coupling (and the frequency shift) is maximum when one of the SRRs of the tag is just on top of the SRR of the reader, with perfect alignment and opposite orientation, i.e., rotated 180° [see Fig. 2(b)].

Therefore, by setting the frequency of the feeding signal to $f_c$ (the resonance frequency of the unloaded reader), the excursion of the amplitude of the envelope function at the output port is expected to be high.

The tags are linear chains of identical SRRs, where each SRR provides a bit of information. Such tags can be either programmed, by cutting the resonant elements associated to the logic state '0' (making them inoperative), or erased, by short-circuiting the cut SRRs through inkjet (thus adding conductive ink in order to set the corresponding bit to '1'). This approach is different from [9],[10], where encoding was achieved by the presence/absence of resonant elements at the predefined and equidistant positions in the tag. The main advantage of tag programming/erasing is the possibility of massive manufacturing of all-identical tags, thus reducing fabrication costs. Once fabricated, tags can be programmed in a later stage, and erased and re-programmed as many times as needed.

## III. Orientation-Independent Tag Reading

Another relevant aspect of the proposed tags is the fact that tag reading is independent of their orientation with regard to

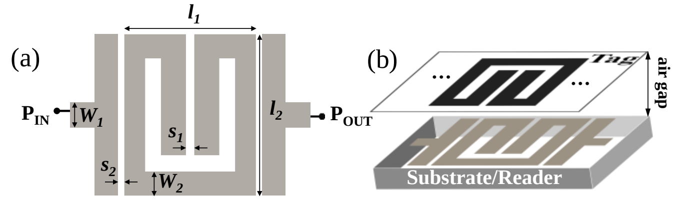


Fig. 2. Layout of the active part of the reader (a) and 3D view of the loaded reader with one of the SRRs of the tag aligned with the SRR of the reader (b). Dimensions are (in mm): $l_1$ = 3.16, $l_2$ = 3.35, $s_1$ = 0.2, $s_2$ = 0.2, $W_1$ = 0.56, and $W_2$ = 0.5. The distance between adjacent SRRs in the tag chain is 0.2 mm.

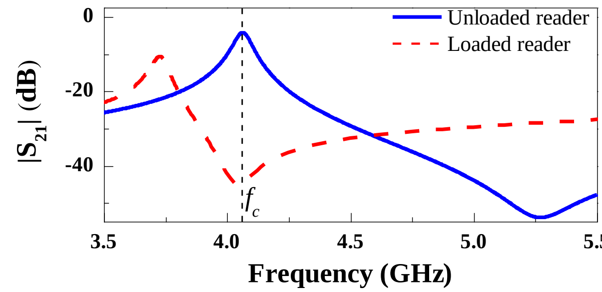


Fig. 3. Magnitude of the transmission coefficient ($S_{21}$) of the unloaded reader and reader loaded with the tag with one of the SRRs perfectly aligned with the SRR of the line, considering an air gap of 0.25 mm. These results have been inferred by electromagnetic simulation, using *Keysight Momentum*.

the reader, i.e., tag reading is either possible by displacing the tag over the reader with the resonator chain printed on the top (face-up) or the bottom (face-down) side of the tag substrate. To this end, two pair of bits (header bits) have been added at the beginning (sequence '11') and at the end (sequence '10') of the tag code, as depicted in the fabricated tag of Fig. 4. Such tag, with all ID bits set to '1' (all resonators functional), has been inkjet printed on paper substrate. The dielectric constant and loss tangent of this paper, with thickness $h$ = 215 μm, have been inferred by means of a split cylinder resonator (model *Agilent 85072A*). The resulting values have been found to be $\varepsilon_r$ = 3.11 and tan$\delta$ = 0.039. The used inkjet printer is *Ceradrop Ceraprinter X-Serie*, and one layer of *Dupont™ PE410* conductive ink (with conductivity 7.28x$10^6$ S/m) has been printed in order to achieve a measured thickness of 2.6 μm.

As mentioned before, to achieve maximum coupling between the SRR of the reader and the SRRs of the tag (thus achieving a high modulation index in the output signal), the relative orientation of both resonant elements must be 180°. Therefore, tag guiding over the reader must be carried out in the form specified in Fig. 2(b), either with the tag SRRs faced up or down. These two scenarios are distinguished by the fact that tags are read following inverse sequences, which justifies the need of header bits. In a real-scenario, the tags must be printed at the edge of the paper, as illustrated in Fig. 1. Hence, the two un-readable tag orientations, with reader and tag SRRs identically oriented, are automatically avoided.

## IV. Experimental Validation

The response of three generated 40-bit tags (see Fig. 5), programmed by cutting several resonant elements (Fig. 6 (a) shows a zoom of an SRR cut), with faced up and faced down orientation have been measured in order to validate the

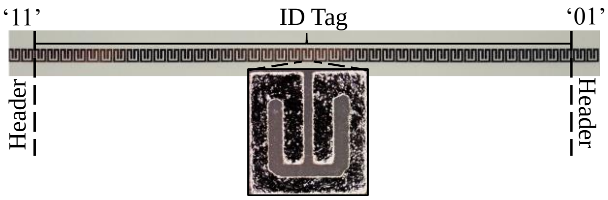


Fig. 4. Photograph of the fabricated 40-bit tag with all bits set to the logic state '1'.

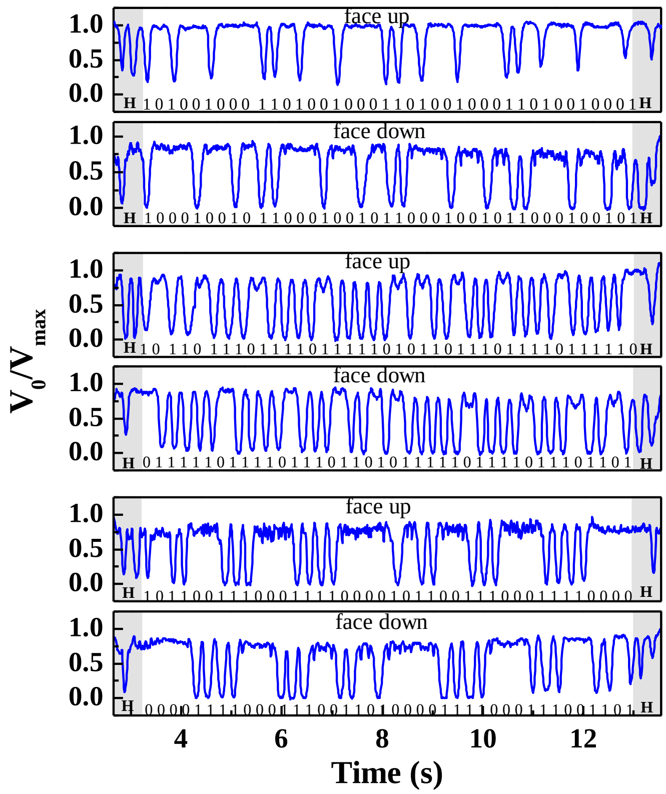


Fig. 5. Measured normalized envelope for the 40-bit programmed tags with the indicated codes.

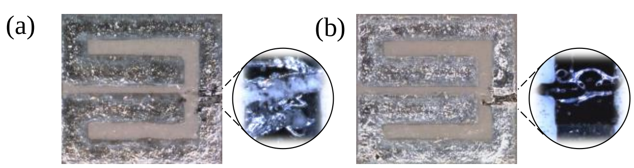


Fig. 6. Zoom of a programmed (cut) SRR (a) and erased (short-circuited) SRR (b), the latter achieved by adding conductive ink.

proposed chipless-RFID system, with programmable/erasable tags and orientation-independent near-field tag reading. Note that the header bits (the first two bits of the tag) provide the information relative to tag positioning, with sequences '11' and '10' corresponding to face up and face down orientations, respectively. Such responses have been obtained by means of the experimental setup available in our laboratory. The carrier signal (with frequency $f_c$ = 4 GHz) is generated by means of the *Agilent E44338C* signal generator and the *Agilent MSO-X-3104A* oscilloscope is used for tag readout. The envelope of the amplitude modulated signal at the output of the transmission line is extracted by means of an isolator (*ATM ATc4-8*), used to prevent reflections, and a Schottky diode (*Avago HSMS-2860*), acting as envelope detector.

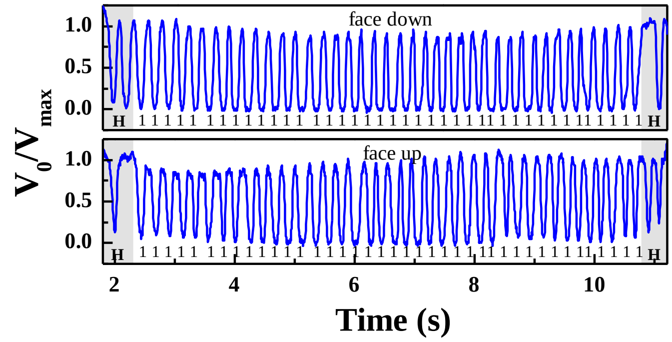


Fig. 7. Measured normalized envelope for the 40-bit erased tag.

Additionally, the measured response depicted in Fig. 7 demonstrates that the tags can be erased by short circuiting those resonant elements previously cut [see Fig. 6(b)]. Although tag erasing in chipless-RFID systems is unusual, this may be useful either for further tag reprogramming, or for correcting errors generated during tag encoding.

## V. Conclusions

In conclusion, a chipless-RFID system based on near-field coupling and sequential bit reading has been validated by reading several codes generated by programming and erasing a single 40-bit tag inkjet-printed on a paper substrate. Such tags exhibit two important features: (i) they can be programmed and erased, and (ii) tags can be read either faced up or down with regard to the reader. The former aspect is relevant in applications requiring thousands of tags, since a single mask at fabrication level (for the implementation of all-identical tags) is required (hence saving costs), and leaving tag encoding (programming) to a later stage (custom level).

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