Chipless RFID Tag Based on Electrically Small Spiral Capacitively Loaded Dipole

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***Abstract*—This letter presents the novel 20 bit chipless radiofrequency identification transponder (tag) based on spiral capacitively loaded dipole scatterers of electrical size $ka = 0.47$, radar cross-section (RCS) $\sigma = -29.3$ dBsm, and bandwidth $BW_{3\mathrm{dB}} = 20.9$ MHz. It outperforms U-folded dipole scatterer ($ka = 0.79$, $\sigma = -34.3$ dBsm, $BW_{3\mathrm{dB}} = 18.1$ MHz) in the first two parameters in exchange for a slight increase in bandwidth. The total tag size (17×68 mm^2) is roughly half the size of a credit card. The frequency and amplitude stability of its RCS response, when the zero bit information is coded via removal of individual scatterers, is improved by reordering scatterers in the array. The simulated results were verified by the monostatic measurement of tag RCS.**

***Index Terms*—Capacitively loaded (C-loaded) dipole, chipless radio-frequency identification (RFID), electrically small dipole, radar cross-section (RCS), scatterer.**

I. Introduction

THE radio-frequency identification (RFID) stands for the technology with various possibilities of application primarily in logistics, commerce, industry, and health care [1]. It is expected to play an important role in the Internet of Things concept mainly for sensing purposes [2], [3] and wearable solutions [4], [5].

Further proliferation of RFID technology is limited by relatively high prices of RFID transponders (tags), which contain semiconductor chips. Methods of identification information storage without any chip being used are generally known as chipless RFID [6] and represent a promising way of reducing tag costs. The most investigated chipless tag solutions are based on the frequency domain detection, using the tag's specific spectral signature. These layouts potentially enable low-cost production of tags by means of conductive ink printing. Each tag consists of an array of differently tuned resonant elements called scatterers [7]–[12]. The principle of information encoding can be described as either presence or absence of each scatterer's peak in tag's spectral signature, representing the logical one or zero, respectively.

Each frequency domain scatterer, suitable for the design of chipless tag, can be described by two principal quantities depending on its electrical size ka, i.e., the radar cross-section (RCS) level of scatterer's resonance peak (determining the reading range) and quality factor Q determining the 3 dB bandwidth ($BW_{3\mathrm{dB}}$) of resonance peak. The smaller the electrical size ka, the lower the RCS and, concurrently, the lower $BW_{3\mathrm{dB}}$. This enables to attain a higher spectral bit capacity, though at the expense of read range scale. The analysis of suitability of various scatterers for chipless RFID transponder design was published in [13].

Another issue to be solved is represented by the strong mutual coupling between the neighboring scatterers, which results in variations in both, frequency position and amplitude levels of resonant peaks, especially in the case of encoding zero bits into the bit word [14], [15].

In this letter, a novel electrically small spiral capacitively loaded (C-loaded) dipole scatterer is presented. Its advantage over the already published U-folded scatterer [9] consists in the smaller electrical size and higher RCS, which is beneficial for both, the spectral bit capacity and spatial bit density. The scatterer design also reflects a mutual coupling minimization, which ensures the frequency and amplitude stability of RCS response. The scatterer suitability for chipless RFID design was investigated using an assembly of 20 bit tags manufactured on 0.1 mm thin microwave dielectric substrate. With regard to the current advancement in conductive ink printing technology, it can be supposed that achievable tolerances of this promising technology will enable mass production of the presented structure in the near future. To verify the simulated results, the monostatic measurement of tag RCS was taken with the help of VNA and double ridge horn antenna [16].

II. Chipless RFID Tag Design

A. Scatterers Geometry and Performance

The U-folded dipole scatterer [9] consists of two parallel arms, which are connected to each other at one end [see Fig. 1(a)]. The widths of all lines equal to 1 mm and the distance between arms accounts for 0.5 mm. The length of arms, which determines the required resonance frequency (the arm length is similar to one quarter of resonant wavelength), is equal to 20.5 mm. The said scatterer shows a sufficient

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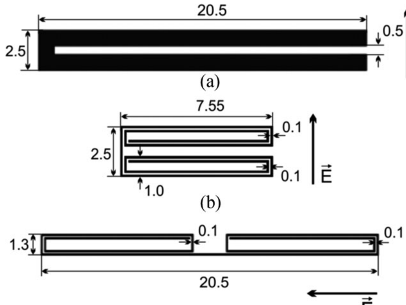

Fig. 1. Scatterer layouts (in identical scale). (a) U-folded dipole scatterer [9]. (b) U-folded spiral loaded by capacitively dipole scatterer. (c) Spiral C-loaded dipole scatterer. All dimensions are stated in mm. Polarization of excitation field is denoted by E-field vector arrow.

TABLE I
PARAMETERS OF INVESTIGATED SINGLE SCATTERERS

	f_r (GHz)	Area (mm^2)	Ka (–)	σ (dBsm)	BW_{3dB} (MHz)	BW_{3dB} (%)
U-folded dipole [9]	3.66	51.3	0.79	–34.3	18.1	0.49
C-loaded U-folded dipole	2.56	18.9	0.21	–58.9	19.4	0.76
C-loaded dipole	2.194	20.7	0.47	–29.3	20.9	0.95

RCS equal to –34.3 dBsm and a narrow bandwidth $BW_{3dB} =$ 18.1 MHz (0.49%). However, its disadvantage is embodied in a mediocre factor $ka = 0.791$ [see Table I]. The performance of all investigated scatterers was simulated in a free space using MoM IE3D software.

One of the most forthright design approaches to lower the ka factor of U-folded dipole is to add spiral endings, which can be described as capacitive loads. In order to fit the spirals between U-strips, the width of all lines is reduced to 0.1 mm. It stays within the tolerance limit of common photo-etching technology. The scatterer occupies the rectangle area of 7.55 × 2.5 mm^2. The spacing between arms is equal to 0.1 mm and the width of spirals amounts to 1 mm [see Fig. 1(b)]. The high level of electric length reduction ($ka = 0.213$) of the respective scatterer is attained in exchange for the inappropriate level of σ = –58.9 dBsm. The bandwidth $BW_{3dB} = 19.4$ MHz (0.95%) slightly exceeds the U-folded dipole value (see Table I). Such a scatterer cannot be used for chipless tag assembling due to an overly low RCS.

The necessary RCS improvement is reached after the U-folded shape is abandoned [see Fig. 1(c)]. The spiral C-loaded dipole scatterer then occupies the rectangle area of 20.5 mm × 1.3 mm. The width of all lines is 0.1 mm, while the spacing between spiral arms accounts for 0.1 mm. The distance between spiral endings is equal to 2 mm. The last scatterer shows σ = –29.3 dBsm and $BW_{3dB} = 20.9$ MHz. These values are comparable to those of a basic U-folded dipole, yet its level of electric length reduction ($ka = 0.472$) is considerably better (see Table I).

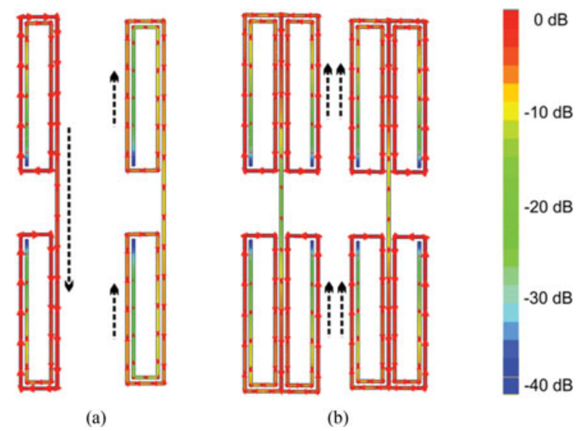

Fig. 2. Simulated currents distribution of spiral C-loaded dipole scatterers pair in (a) asymetrical and (b) symmetrical geometry. Dashed arrows denote orientation of adjacent strips currents.

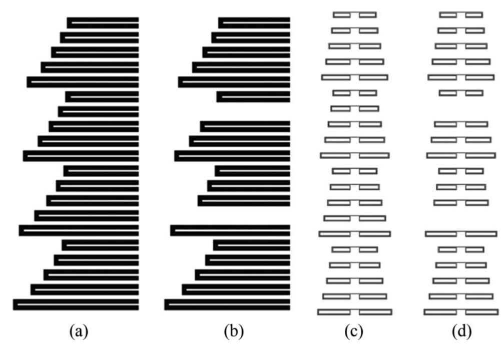

Fig. 3. Layouts of 20 bit chipless tags composed of array of U-folded dipoles (a)-(b) [9] and half-spiral C-loaded dipoles (c)-(d), both using rearrangement published in [14] and both encoding bit words "11111111111111111111" (a, c), and "11111011111111011111" (b, d).

B. Tag Geometry and Performance

The principle of chipless RFID tags based on the frequency domain method is to encode the bit information into tag's RCS response, which consists of a series of resonant peaks of particular scatterers. Presence or absence of the peak/scatterer represents one or zero bit, respectively. Due to its negative influence on the amplitude uniformity and frequency stability of the RCS response peaks, it is necessary to minimize especially the mutual coupling between neighboring scatterers in the tag, so that a high-tag readability is achieved. The geometry of spiral C-loaded dipole is asymmetrical around the axis of incident electric field [see Fig. 1(c)]. This is convenient for mutual coupling reduction as the currents of adjacent strips of the closest scatterers are oriented in opposite directions (see Fig. 2). The symmetrical version of dual-spiral C-loaded dipole was also investigated, yet its mutual coupling is excessively strong. As a consequence, the said scatterers can be used exclusively for tag assembly in diagonal arrangement, which is highly inefficient from the spatial point of view [13], [15].

In order to encode the 20 bit information, the array of 20 spiral C-loaded dipoles (each of them having a slightly different resonance frequency) is proposed to operate within the frequency range of 2.0–3.6 GHz [see Fig. 3(c)]. The tag size is 16.7 × 67.8 mm^2. The simulated tag performance is

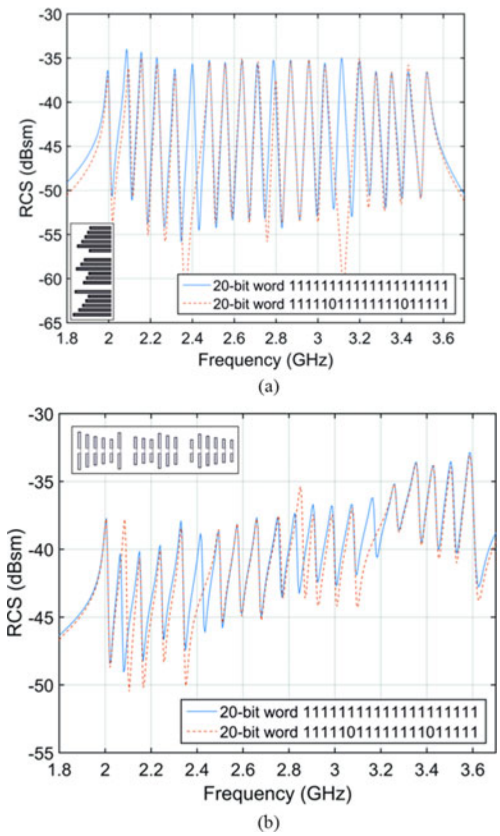

Fig. 4. Simulated RCS responses of 20 bit chipless tags composed of array of U-folded dipoles (a) [9] and half-spiral C-loaded dipoles (b), both encoding bit words “11111111111111111111,” and “11111011111111011111.”

TABLE II
PARAMETERS OF INVESTIGATED 20 BIT TAGS

Scatterer of the transponder	RCS Min/Max [dBsm]	Min Peak-to-Valley Difference [dB]	Spectral Bit Capacity [bit/GHz]	Space Bit Density [bit/cm^2]	Uniformity of RCS Response
U-folded dipole [9]	–37/–34	1.3	13.1	0.98	good
C-loaded dipole symm.	–38/–34	4.5	10.0	0.22	avg.
C-loaded dipole asymm.	–41/–30	2.1	12.5	1.77	Quasi-monotonously increasing

compared with the one of the tag consisting of 20 U-folded dipoles [14] designed for the same frequency band [see Figs. 4 and 3(a), and Table II]. The size of U-folded dipole tag is, however, approximately twice as large, i.e., 29.5 $\times$ 69 mm^2. The lengths of both scatterer types are designed so they reach approximately 80 MHz frequency spacing between neighboring resonance peaks. The distances between each two neighboring elements are 1 and 2.2 mm for, respectively, the U-folded dipole tag and the one using spiral C-loaded dipoles

For additional improvement in amplitude uniformity as well as frequency stability of RCS response (RCS response robustness) by reducing the mutual coupling between neighboring scatterers, a modification of scatterer arrangement proposed in [14] is used in both tag designs. The scatterers are divided into four subarrays, where each element is next to the one that was originally in fourth position from it. Consequently, the original ascending order according to the element length “1 2 3 4 5 6 7 ... 20” is modified to “1 5 9 13 17, 2 6 10 14 18, 3 7 11 15 19, 4 8 12 16 20” (see Fig. 3). In this layout, the resonators with neighboring resonance frequencies are, then, located further apart, which gives rise to a substantial reduction in their coupling.

The performance of both tags is investigated for two different bit words in order to prove that the impact of mutual coupling on RCS response stability does not prevent reading of tags. The tags containing 20 scatterers represent the bit word “11111111111111111111,” whereas the tags with only 18 scatterers encode the bit word “11111011111111011111” [see Fig. 3(a), (c) and (b), (d), respectively].

The incident excitation field is parallel to the dipole lengths in the case of spiral C-loaded dipole tag and perpendicular to the dipoles arms in the case of U-folded dipole tag (see Fig. 1). The tags performance was simulated on the low-loss dielectric substrate Rogers RO4350 ($\varepsilon_{\mathrm{r}} = 3.66$, $\tan\delta = 0.003$) with the thickness of 0.254 mm (see Fig. 3). The same substrate was also used to manufacture the tags in order to verify the simulated RCS responses by the monostatic measurement.

The resonant peaks of simulated RCS response of U-folded dipole tag, which encodes the basic bit word “11111111111111111111” differ at the most by 2 dB [see Fig. 4(a)]. Moreover, we can observe 2 dB differences in comparison to responses of different bit words in Fig. 4(a). This arises from resonant peaks number ”2” and “11.” Likewise, in the said peaks, there are resonant frequency shifts amounting to ca. 10 MHz that are not vital for information reading though. The respective peaks belong to scatterers that are adjacent to the removed scatterers number “6” and “15” [see Fig. 3(b)]. The difference between the resonant maxima and minima ranging from 14 to 20 dB was obtained in simulations only. The measured values vary between 3 and 10 dB [14].

The resonant peaks of simulated RCS response of spiral C-loaded dipole tag differ at the most by 7 dB, i.e., in the case of bit word containing only logical ones [see Fig. 4(b)]. Nonetheless, the RCS curve shows a quasi-monotonous rise and is quite stable when different bit words are encoded. The cause of the rise is currently rather unclear. The deeper analysis, e.g., numerical, of this effect falls outside the intended scope of this letter. However, it is likely to be related to unequal size relations of the loaded spiral and dipole length with frequency tuning.

Hence, for reading purposes, it would be simple to compute different thresholds for each resonant peak in order to make a logical value decision. The peak-to-valley value ranges from 3.5 to 10 dB. The information encoding conducted via scatterer removal also results in shifts in RCS magnitude and resonant frequency of the peak numbers “2” and “11.” The respective peaks belong to resonators next to the removed ones (“6” and “15”). The peak amplitude shift accounts for approximately 2 dB, while the frequency shift is equal to 25 MHz, which is acceptable from information reading point of view as well.

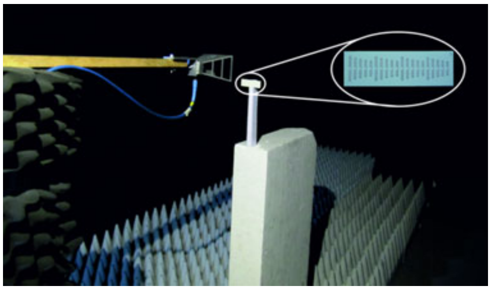

Fig. 5. Monostatic measurement configuration in anechoic chamber, detailing 20 bit tag using half-spiral C-loaded dipoles.

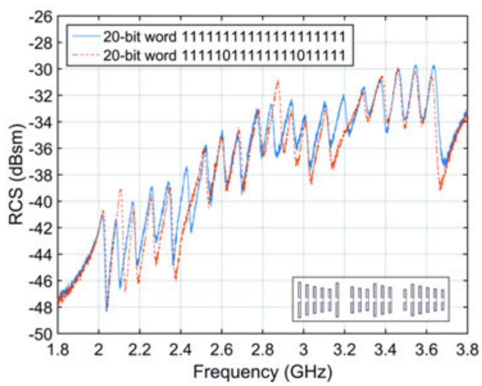

Fig. 6. Measured RCS response of 20 bit chipless tags using rearanged half-spiral C-loaded dipoles, representing bit words "11111111111111111111," and "11111011111111011111."

III. Measurement

To verify the simulated results, we made the monostatic measurement of tags RCS performance in an anechoic chamber (see Fig. 5). It was based on the reflection coefficient evaluation of the double ridge horn antenna DRH20 [16] in front of which a scatterer at a distance of 150 mm was placed. The tag's RCS response was calculated with the help of the relation used in [9] and modified so that it was applicable to the one-port case described in [14].

Fig. 6 depicts the measured RCS response of 20 bit chipless tag, which consists of rearranged spiral C-loaded dipoles encoding two bit words [see Fig. 3 (c) and (d)]. They are identical to the simulated ones mentioned above. The RCS levels of resonant peaks range from –41.5 to –30 dBsm. The decision threshold for bit evaluation can be set as (in parts) monotonously constant or increasing curve interleaving the resonant peaks. It is conspicuous in both, the simulated and measured results. The peak-to-valley value ranges from 2 to 7 dB, which is slightly less than in simulation. The response of bit word "11111011111111011111" suffers from a minor distortion in comparison to the full word "11111111111111111111," which is similar to the simulated one. In general, the measured and simulated responses sufficiently correspond to each other.

IV. Conclusion

The novel 20 bit chipless RFID tag based on the frequency domain detection, consisting of electrically small spiral C-loaded dipole scatterers was proposed, developed, and verified. As the dipoles were loaded at the ends by spirals, the footprint size could be reduced to only 11.3 cm^2 (spatial density 1.77 b/cm^2). It is necessary to note that the reference 20 bit tag [9], [14] was 20.4 cm^2 in size (i.e., spatial density 0.98 b/cm^2). This significant size reduction was attained while maintaining comparable parameters of the spectral bit density and RCS response level. Hence, there is a negligible disadvantage of the proposed tag, consisting in a quasi-monotonous rise of curve interleaving resonant peaks in RCS response, ranging from –41.5 to –30 dBsm. This nonuniformity can be considered a minor obstacle to the tag reading, because the response is stable enough for different encoded bit words. Moreover, different logical values of decision threshold RCS levels for each resonant peak can be easily computed owing to linear nature of the nonuniformity. The peak-to-valley RCS values of novel tag are slightly lower (approx. by 1 to 3 dB) than in the case of U-folded dipole tag. However, its readability remains sufficient owing to the minimization of mutual coupling, achieved via asymmetrical layout of the novel scatterer and its rearrangement in the tag.

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