26th Conference Radioelektronika 2016, April 19-20, Košice, Slovak Republic

Capacitively Loaded Dipoles for Chipless RFID Transponder

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***Abstract*—This paper proposes a novel uniplanar capacitively loaded dipole-scatterers as building elements for chipless RFID tags with frequency domain coding information. These elements are compared with the known structures in terms of quantities which are crucial for read range (radar cross-section), coding bit capacity (resonance bandwidth), and electrical size. Most suitable type of scatterer was arranged into a 5-bit tag, manufactured and verified by measurement in anechoic chamber.**

***Index Terms*—Chipless RFID; radar cross-section; scatterer; spectral response coding**

1. INTRODUCTION

Radiofrequency identification (RFID) is widespread technology which is used more and more often in industry, logistics, commerce and health care. There is a significant opportunity for further spreading in commerce if RFID tags would be suitable for optical barcode replacement. Advantage of the tag is possibility to be read without necessity of clear line of sight. Low price of the tag is essential for reaching this goal. Unfortunately conventional tags which consists a chip are about hundred times more expensive than barcode [1]. Perspective approach to reduce the tag cost is chipless RFID which provides different methods of storing information without chip. Chipless tags based on spectral signature [1-3] which in most cases consist of resonators are a promising example of this technology. Presence or non-presence of each resonator's peak in tag's spectral signature represents logic one or zero, respectively. The main issue of this approach that must be solved is in low bit capacity of the tags, above all. Chipless RFID tags can be also used as a sensor [4].

There are many different types of planar resonators which can be used as a basic building unit of the tag. There are three important quantities, which must be evaluated for each resonator which is considered for chipless RFID usage. First of them is radar cross-section (RCS) which determines the reading range of the tag. The higher RCS results in the longer reading range. Second quantity is bandwidth (BW) of resonance peak which depends on quality factor of resonance, it can be evaluated from frequency characteristic of the resonator as frequency range of three decibel resonance peak drop. This value is important from spectral bit capacity point of view. For example when bandwidth is 200 MHz there can be stored only five bits for each GHz in the spectrum. Last quantity is product ka where k is wave number and a is radius of circle circumscribed the resonator. This quantity represents rate of electric reduction of the resonator. Resonators with ka below one are suitable candidates because small scale is essential for purposes of chipless RFID.

There are several uniplanar (can be printed) capacitively loaded scatteres proposed in this paper which are compared with some older ones from chipless tag usage point of view. Important quantities which were mentioned before were evaluated by simulations. One of perspective resonators was used to assemble 5-bit tag which performance was also verified by measuring.

2. SCATTERERS AND THEIR PROPERTIES

Proposed resonators have a simple geometry and their performance is shown for mainly reference purpose, see Figs. 1 - 3. Examples of this category are half-wavelength planar dipole (length 37 mm, 1 mm in width), circular ring (diameter 10 mm, line width 1 mm, split length 2.3 mm), rectangular loop (side 10 mm, line width 1 mm, split length 2.5 mm), meander dipole (total length 56 mm, meander length 6 mm, line width 1 mm, distance between meanders 1 mm) and thick U dipole (arm length 20.5 mm, line width 1 mm, distance between arms 0.5 mm), proposed in [5]. There are another three scatterers which are based on the thick U dipole. It's thin dipole (arm length 20.5 mm, line width 0.25 mm, distance between arms 2 mm) which was proposed in [6], U dipole with skew arms (arm length 20.5 mm, line width 0.25 mm, distance between skew arms at their open ends 0.5 mm) which was also proposed in [6] and meander U dipole (arm length 20.5 mm, line width 0.25 mm, meander length 5 mm, distance between meander arms 0.2 mm, distance between dipole arms 2 mm). Analogical scatterer was proposed in [7]. Last group of scatterers are represented by several capacitively loaded dipoles and one inductively loaded dipole (ILD). All these

This work was supported by Czech Science Foundation under projects GA15-08803S, GA13-09086S, and partially by COST project No. LD 14 122 WiPEELMAG “Electromagnetic Structures and Circuits for Wireless Power Transmission”, which form a part of COST project No. IC 1301 WiPE: “Wireless Power Transmission for Sustainable Electronics”.

scatterers occupy a rectangle area 20.5 mm by 2.5 mm. ILD consists of 18 skew parts. Spacing between them and arms 9.25 mm in length is 0.23 mm, line width is 0.25 mm and length of straight part in the middle of scatterer is 2 mm. Basic capacitively loaded dipole (CLD 1) consists just dipole part and four ending arms 9.25 mm in length each. Spacing between dipole part and arms is 0.88 mm and width of all lines is 0.25 mm. Version labeled as CLD 2 is based on CLD 1 and four inner arms were added (length 8.75, spacing between dipole part and inner arms is 0.38 mm, spacing between outer and inner arms is 0.26 mm). Capacitively loaded dipoles can be divided into two groups. The difference is in mutual linking of ending arms which can be either mender or spiral shaped. There are three arm versions labeled as 'M 3 arm' and 'S 3 arm' which are an extension of CLD 2 (arms width as well as spacing between them was reduced to 0.18 mm). Thin versions (M 5 arm and S 3 arm v2) have five and three arms respectively and their line width as well as spacing between arms is 0.1 mm. Layouts of all proposed scatterers are shown in Figs. 2 and 3. All scatterers were designed on RO4003 substrate (ε_r = 3.38, tan δ = 0.002, 0.2 mm in thickness).

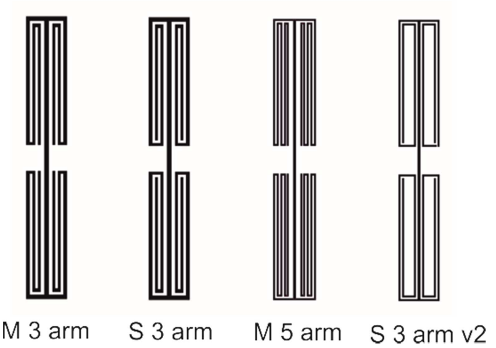

Fig. 1. Detail of proposed scatterers geometry

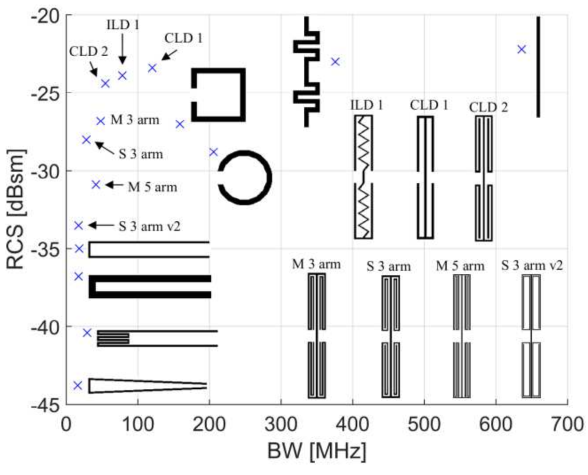

Fig. 2. Comparison of scatterers according the RCS and resonance bandwidth

Theory of electrically small antennas says that resonance structures with small *ka* have high quality factor *Q* which implicates low bandwidth which is beneficial for high spectral bit capacity and low RCS which is inappropriate for reading range. Therefore there is always a trade-off between spectral bit capacity and reading range of the tag. Results of simulations in IE3D software are shown in Table 1. Figs. 2 and 3 confirm this theory.

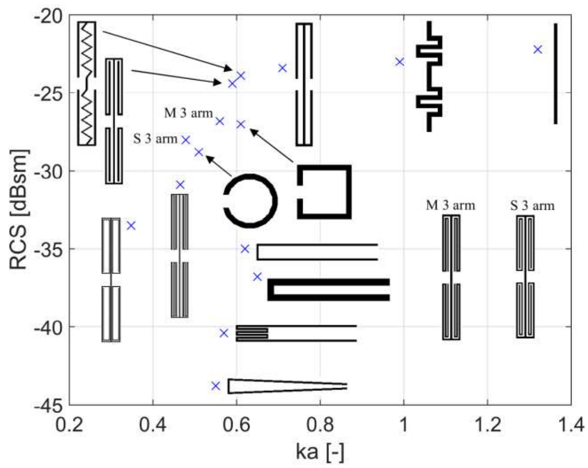

Fig. 3. Comparison of scatterers according the RCS and *ka* product

TABLE I. COMPARISON OF SCATTERERS PROPERTIES

Scatterer	*ka* [-]	f_r [GHz]	RCS_{max} [dBsm]	BW [MHz]
Dipole	1.32	3.400	-22.2	636.0
Circular ring	0.51	4.893	-28.8	205.7
Rectangular ring	0.61	4.085	-27.0	158.8
Meander dipole	0.99	3.555	-23.0	375.6
Thick U dipole	0.65	3.012	-36.8	17.2
Thin U dipole	0.62	2.855	-35.0	18.2
Skew arms U dip.	0.55	2.565	-43.8	16.0
Meander U dipole	0.57	2.623	-40.4	29.2
CLD 1	0.71	3.263	-23.4	120.2
CLD 2	0.59	2.723	-24.4	54.7
M 3 arm	0.56	2.570	-26.8	48.1
ILD	0.61	2.830	-23.9	78.3
S 3 arm	0.48	2.212	-28.0	28.1
M 5 arm (thin)	0.47	2.152	-30.9	41.5
S 3 arm v2 (thin)	0.35	1.609	-33.5	17.2

The lowest BW achieved skew U dipole with 16 MHz, and also other U dipoles reached suitable values. But all of them have RCS below or equal -35 dBsm which makes reading range short, their coefficients *ka* are on average. Capacitively loaded dipoles have better RCS in general (up to -23.4 dBsm) but most of them are insufficient from BW point of view. When comparing CLD 1, CLD 2 and M/S 3 arm scatterers it is noticeable that adding more arms to the scatterer endings results in higher *ka* and lower BW but at the penalty of decreasing RCS. From the comparison of meander/spiral approach it is obvious that spiral scatterer is better for chipless RFID usage. This is caused by orientation of coincident currents in neighbouring arms of the spiral compared to opposite currents in meander arms [8]. Thin variants of meander/spiral scatterers were designed in more than two versions proposed above, but their RCS was too low or BW too high.

3. TAG ARRANGEMENT

The thin spiral three arm scatterer was chosen for the tag design. It's very low BW is an important advantage although RCS is average. A difficult issue for tag assembling is mutual coupling between scatteres. There are two arrangements of 5-bits tag proposed in this paper. Basic serial arrangement, where the mutual coupling is reduced only by l_h = 4.5 mm spacing between neighboring scatteres; see Fig. 4a. Size of this arrangement including 4 mm margins is 38.5 mm by 28.5 mm. Second arrangement is focused on better reducing of mutual coupling by shifting vertically each scatterer by l_v = 21.5 mm; see Fig. 4b. Size of this arrangement with same margins is 24.5 mm by 113 mm. Scatteres with higher resonance frequency were design by reducing appropriately the length of the basic element (described in section 2). Frequency spacing between resonances is 100 MHz in both cases; see Fig. 5.

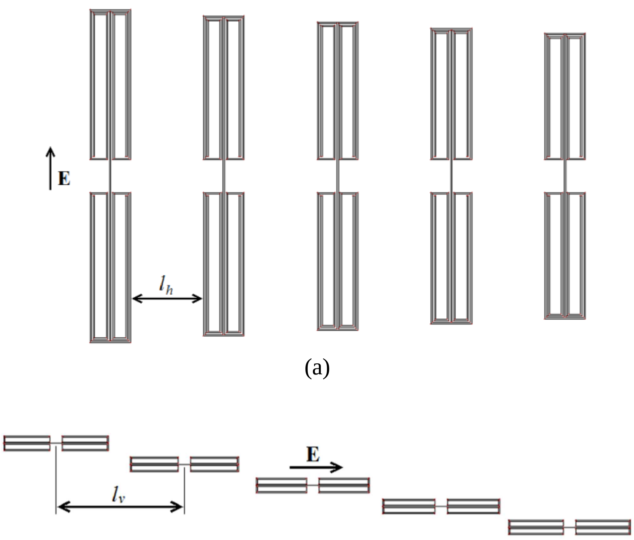

Fig. 4. Designed 5-bit tags with horizontally shifted arrangement (a) and vertically shifted arrangement (b)

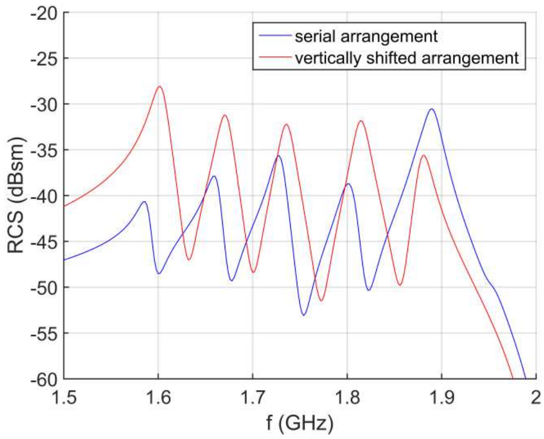

Fig. 5. Simulated performance of 5-bit tags in both arrangements

The differences in amplitudes of each resonance and also (much less significant) shifts in their frequency are obvious consequences of the mutual coupling in serial arrangement. These differences are more remarkable in horizontal arrangement. Another consequence of the strong mutual coupling of this arrangement is saw-toothed shape of the resonances.

4. MEASUREMENT OF TAG PERFORMANCE

To verify the simulated results of the 5-bit tags, we performed the monostatic measurement of tag RCS performance in an anechoic chamber. The measurement was based on the evaluation of reflection coefficient of a double ridge horn antenna DRH 20 [9] in front of which a scatterer at a distance of 0.3 m was placed. The calculation of RCS response of the tag was performed by the equation used in [5] and modified so that it was applicable to the one-port case

$$\sigma^{tag} = \left(\frac{S_{11}^{tag} - S_{11}^{iso}}{S_{11}^{ref} - S_{11}^{iso}} \right)^2 \sigma^{ref} , \qquad (1)$$

where S_{11}^{tag} is the reflection coefficient of the measured tag. S_{11}^{ref} represents the reflection coefficient, of the reference plate used as a scatterer. S_{11}^{iso} is the reflection coefficient of antenna itself in case that no scatterer is used, and comprises the residual reflection from the experimental surroundings. σ^{tag} is the RCS of the measured tag, σ^{ref} is the RCS of the reference scatterer, which is the rectangular metal plate 100×100 mm^2 in size and 0.3 mm in thickness. Its analytical formula for RCS is:

$$\sigma^{ref} = 4\pi \frac{a^2 b^2}{\lambda^2} . \qquad (2)$$

Result of measurement is plotted in Fig. 6. The RCS responses of two variants of 5-bit chipless RFID tags show the same properties which was mentioned in section 3. Amplitude differences in resonances of the serial arrangement are more significant in measurement results than in simulated ones. Frequency shift approx. 20 MHz and amplitude difference roughly 5 dBsm between simulated and measured data are presented. This is namely caused by limitation of simulation where an infinite substrate in method of moments is used while the real footprint size of supporting dielectric plate is $28 \times 44\ \text{mm}^2$ (for serial arrangement) or $24 \times 112\ \text{mm}^2$ (for vertically shifted arrangement).

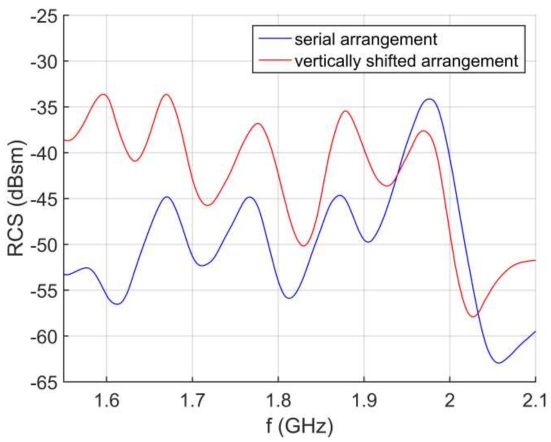

Fig. 6. Measured performance of 5-bit tags in both arrangements

5. CONCLUSION

The paper discusses behavior of particular planar resonators proposed as building blocks of RFID chipless tags work in in the frequency domain mode. It has been shown that proposed capacitively loaded dipole scatterer exhibits higher value of RCS, smaller electrical size and comparable bandwidth comparing to currently known strip-type scatterers and that is why they are suitable candidates for building elements of chipless RFID transponders. It is essential to propose an arrangement minimizing mutual coupling between particular scatteres for the high bit capacity tag design.

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