Abstract: The study deals with the novel polarisation-independent 20-bit chipless radiofrequency identification (RFID) transponder that is based on a circularly arranged array of electrically small dual-spiral capacitively-loaded dipole scatterers with improved robustness of radar cross-section (RCS) response. A single scatterer exhibits a better performance in terms of electrical size and RCS than the earlier introduced U-dipole type scatterers occupying the same footprint area. In order to investigate the frequency stability and amplitude uniformity of RCS curve, two arrangements of scatterer arrays were analysed: rearranged side-by-side and circular. In comparison to the other arrangements, the latter provides an excellent amplitude RCS stability over the whole operational frequency band and, at the same time enables the polarisation independence of identification. However, it requires the two-channel orthogonal polarisation measurement.

1 Introduction

The passive radiofrequency identification (RFID) represents a widespread technology, successfully employed in many areas of human activities. It is gradually extending to more complex applications, for instance the operation in the close vicinity of lossy dielectric and metallic objects or human body, integration of RFID applications, for instance the operation in the close vicinity of lossy dielectric and metallic objects or human body, integration of RFID

<table>
<thead>
<tr>
<th>Reference</th>
<th>Frequency range, GHz</th>
<th>RCS, dBsm</th>
<th>Minimum peak value, dB</th>
<th>Spectral bit capacity, bit/GHz</th>
<th>Spatial bit density, bit/cm²</th>
<th>Spatial bit density, bit/λ²</th>
<th>'0'-bits reliable coding verification</th>
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<tr>
<td>[10]</td>
<td>2–8</td>
<td>−20</td>
<td>3</td>
<td>1.7</td>
<td>0.5</td>
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<td>−20</td>
<td>1</td>
<td>2.5</td>
<td>2.1</td>
<td>63.2</td>
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<tr>
<td>[12]</td>
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<td>−15</td>
<td>5</td>
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<td>0.2</td>
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<td>[13]</td>
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<td>−32</td>
<td>4</td>
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<td>19.0</td>
<td>142.3</td>
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</tr>
<tr>
<td>our design</td>
<td>1.8–3.6</td>
<td>−33</td>
<td>4</td>
<td>12.5</td>
<td>0.7</td>
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investigated in the rearranged side-by-side and circular scatterer of the same footprint size [9], it exhibits substantially development versions and simple straight dipole (in scale) (see Figs. 1 and 2). Compared to the thin strip U-dipole type stability and polarisation independence at the expense of two-the study of RCS performance of scatterer development versions, improvement of parameter performance of the chipless RFID tag small dual-spiral capacitively-loaded dipole scatterer (DS CLD) (see Figs. 1 and 2). The performance parameters of DS CLD tags were investigated (in scale) smaller electrical size $ka$ (0.35 versus 0.62), a bit higher RCS level ($-33.5$ versus $-35.0$ dBsm) and comparable 3 dB bandwidth (17.2 versus 18.2 MHz).

The bit information encoding in the case of frequency-domain chipless RFID tags is provided by means of presence/absence of resonant peaks/valleys of particular scatterers in tag's RCS response.

A strong mutual coupling between neighbouring elements of scatterers array negatively affects the amplitude uniformity and frequency stability of the RCS response [14, 15]. As a consequence, the topology configurations of the array minimising the adjacent element mutual coupling are highly desirable. The skew half-wave dipoles [21] are known for showing reduced mutual coupling for the same distance of dipole centre compared to the side-by-side configuration [22]. Such configuration of DS CLD was considered here for the circular array tag design, which further exhibits polarisation independence.

The current distribution of DS CLD dipole pairs in the side-by-side and skew dipole configurations are depicted in Fig. 3. The latter exhibits the dipole centre value $h$ in the case of slight radial shift, which is due to the dipole placement on two different radii from the centre of circular configuration (see Figs. 3b and 4). Both configurations were excited by the incident plane wave of the frequency corresponding to the resonance of shorter dipole. The electric field vector $E$ to the dipole axis was inclined by $9^\circ$. It can be observed that the lower the mutual coupling of skew dipole configuration, the lower the current density of adjacent longer dipole (in comparison to the side-by-side configuration; see Fig. 3a).

In this paper, a novel circular arrangement of 20-bit electrically small dual-spiral capacitively-loaded dipole scatterer (DS CLD) array with improved robustness of RCS response is presented. Several capacitively loaded dipole scatterers originally proposed in [15] are compared to a simple straight dipole to evaluate their RCS uniformity of the chipless tag RCS curve, the scatterers were investigated in the rearranged side-by-side and circular arrangements. They both enable the reduction in mutual coupling. In addition, the latter one also ensures excellent RCS amplitude stability and polarisation independence at the expense of two-channel orthogonal polarisation measurement.

2 Topology and arrangement of scatterers in chipless tag

Given the results of single scatterer analysis [15, 16] completed by the study of RCS performance of scatterer development versions, the DS CLD was chosen as a promising candidate for significant improvement of parameter performance of the chipless RFID tag (see Figs. 1 and 2). Compared to the thin strip U-dipole type scatterer of the same footprint size [9], it exhibits substantially smaller electrical size $ka$ (0.35 versus 0.62), a bit higher RCS level ($-33.5$ versus $-35.0$ dBsm) and comparable 3 dB bandwidth (17.2 versus 18.2 MHz).

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### 2.1 Parametric study of the DS CLD triplets

Apart from the mutual coupling evaluation using current distribution, the coupling effect of RCS response was also illustrated by the parametric study of DS CLD triplets in modified side-by-side as well as circular arrangements (see Figs. 5 and 6, respectively).

It can be observed that the side-by-side arrangement with mutual distance $d = 3.5$ mm of the scatterers embodies parasitic resonances that make the tag resonance unreliable for identification. The parasitic resonances fade-out in the case of dipole distance $d \geq 5$ mm.

Due to the angle-wise inclination and slight radial shift, the circular arrangement enables to locate the neighbouring adjacent scatterers in the close vicinity (angle $\varphi = 13^\circ$), thus the unwanted mutual coupling is reduced. Consequently, the tag size is given only by the size and number of particular scatterers incorporated into the tag.

### 2.2 20-bits tag in side-by-side arrangement

The performance parameters of DS CLD tags were investigated using the arrays of 20 elements (Fig. 7). To reduce the mutual coupling between neighbouring elements, we used a modification of element arrangement proposed in [14]. The elements are divided into four sub-arrays, 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. 7a). In this layout, the resonators with neighbouring resonance frequencies are located further apart and thus their coupling is substantially reduced. However, a small frequency shift can be observed on bit positions '7' and '8' and the RCS response uniformity does not attain satisfactory levels (see Fig. 8).

The outer size of the largest element is equal to 16.7 × 2.5 mm, while the dimensions of the smallest one are equal to 9.7 × 2.5 mm, with the strip width and the gap size of 0.1 mm. The distance between each two neighbouring elements is 1 mm. The tag motif was etched on the low-loss dielectric substrate Rogers RO4350 (\(\varepsilon_r = 3.66, \tan\delta = 0.002\)) with the thickness of 0.254 mm. The incident excitation field is oriented parallel to the dipoles length, i.e. vertically to the tags presented in Fig. 7.

All presented structures were simulated by the method of moment Zeland IE3D software, using the infinite dielectric layer implementation with the mesh density of 20-cells per wavelength. Given that the IE3D enables the structure excitation by means of incident linearly polarised plane wave, the RCS response of circular arrangements (in contrast to the linear one) was evaluated from two orthogonal components according to the relation [23]

\[
\sigma_{dB} = 10\log(\sigma^E + \sigma^H),
\]

where \(\sigma_{dB}\) stands for the simulated transponder RCS stated in dBsm; \(\sigma^E\) and \(\sigma^H\) represent the linear values of simulated transponder RCS in orthogonal polarisation planes, respectively.

### 2.3 20-bits tag in circular arrangement

As it was mentioned above, the mutual coupling between particular scatterers, which can be partly reduced by the re-arrangement described in the previous subsection, represents a drawback of these transponders. The amplitude uniformity and frequency stability can be further enhanced by the placement of scatterers into circular arrangement, the elements being retained in the re-ordered position. As the neighbouring scatterers are situated angle-wise and/or alternatively shifted into the circular pattern centre (Fig. 4), the circular arrangement ensures a further reduction in mutual coupling between the elements.

Fig. 9 depicts the significant improvement in RCS response uniformity as well as frequency stability. In addition, it offers the analysis and comparison of full 20-bits tag and two different tags with pair of zero bits, situated in mutual distant as well as adjacent positions. Partial disadvantages of this solution are represented by the employment of two-channel measuring method and the use of two-port orthogonal-polarised antenna (see Section 3). On the other hand, the polarisation independence and excellent amplitude robustness of RCS response of circularly arranged transponder represent significant benefits.
The outer size of transponder equals 55 × 55 mm. The tag motif was etched on the low-loss dielectric substrate Rogers RO4350 ($\varepsilon_r = 3.66$, $\tan\delta = 0.002$) with the thickness of 0.254 mm. The geometry and outer size of elements are the same as in the linear arrangement described in Section 2.1.

The circular arrangement is composed of the modified DS-CLD scatterers (in line with Fig. 7), whose centres are situated on two concentric circles with radii of 13.5 and 19.5 mm, respectively. This topology enables the separation of major part of each of two neighbouring scatterers, whose $s$ exceed 1 mm. The angle-wise inclination of each two neighbouring scatterers is equal and can be calculated as $360^\circ/N = 18^\circ$ for $N = 20$ scatterers.

2.4 Polarisation independence of circular arrangement

As it was already indicated, the polarisation independence presents a substantial benefit of circular arrangement that was verified by both, simulations and measurements for the full 20-bits transponder representing the bit word ‘11111111111111111111’ (see Fig. 10).

As expected, the RCS responses for rotation angles 0° and 90° are completely identical. Small differences can be observed in the RCS response for the rotation angle 45°, yet the peaks resolution and consequently the bit word identification still attain satisfactory levels.

3 Measurement

To verify the simulated results, we performed the monostatic measurement of tag RCS performance in the anechoic chamber by means of R&S ZVA 40 network analyser within the frequency band ranging from 1.6 to 3.6 GHz. The measurement was based on the evaluation of reflection coefficient of a quad-ridge horn antenna QRH 20 [24] in front of which a transponder at a distance of 0.25 m was placed (see Fig. 11). Reflection coefficients of both antenna orthogonal inputs were measured simultaneously by two-port VNA model. As the far field for the horn aperture diagonal of the size of 0.1 m equals about 0.17 m at 2.5 GHz ($2D^2/\lambda_0$), the condition for evaluation of RCS by measurement was fulfilled.

The calculation of RCS response of the transponder was performed in line with the relation used in [14] and modified so that it was applicable to the two-port orthogonal case that is in line with (1)

$$\sigma_{tag} = 10 \log \left( \frac{S_{v}^{tag} - S_{h}^{iso}}{S_{v}^{ref} - S_{h}^{iso}} \right) + \left( \frac{S_{v}^{tag} - S_{h}^{iso}}{S_{v}^{ref} - S_{h}^{iso}} \right)^2 \sigma_{ref},$$

where $S_{v}^{tag}$ and $S_{h}^{tag}$ are the vertical (port-1) and horizontal (port-2) reflection coefficients for the case that the measured tag is used as a scatterer. $S_{v}^{ref}$ and $S_{h}^{ref}$ represent the reflection coefficients in the case that the reference plate is employed as a scatterer. $S_{v}^{iso}$ and $S_{h}^{iso}$ symbolise the reflection coefficients of antenna itself in the case that no scatterer is used and comprises the residual reflection from experimental surroundings. $\sigma_{tag}$ stands for the RCS of measured tag and $\sigma_{ref}$ embodies the reference scatterer RCS, which is the rectangular metal plate of 55 × 55 mm$^2$ in size (corresponding with the measured tags) and 0.3 mm in thickness. Its analytical formula for RCS is as follows [23]:

$$\sigma_{ref} = 4\pi\frac{a^2 b^2}{\lambda^2}$$

Fig. 12 shows the measured RCS response of 20-bit chipless tag in circular arrangement. Full 20-bits tag and two different tags with pair of zero bits (in distant as well as adjacent positions to each other) were compared (see Figs. 4b and c). Significantly improved RCS response uniformity and a good frequency stability were confirmed. Moreover, the depth of peaks better than 5 dB over the whole operating frequency band can be observed.

The measurement results of RCS response in several different angle orientation confirmed the polarisation independence of circularly arranged transponder (Fig. 13). Contrary to simulations shown in Fig. 10, the RCS response for the rotation angles 0° and 90° are not fully identical in this case. It is due to the non-identical placement of transponder in the measuring position.
We proposed and investigated a novel chipless RFID transponder in circular arrangement, composed of array of DS CLDs in element rearranged configuration representing bit words ‘11111111111111111111’, and ‘11101111110111111111’, respectively. The difference between the measured level of minimum and maximum RCS peak of single tag scatterers equals ∼3, 15, 12 and 3 dB for side-by-side, rearranged side-by-side and element rearranged in circular arrangement, respectively. Furthermore, the proposed solution ensures the polarisation independence of identification, yet at the expense of the necessity to employ the two-channel measuring method.

5 References