Improvement in Robustness and Recognizability of RCS Response of U-Shaped Strip-Based Chipless RFID Tags

Milan Polivka, Member, IEEE, Jaroslav Havlicek, Milan Svanda, and Jan Machac, Senior Member, IEEE

Abstract—The paper presents significant improvement in robustness and recognizability of RCS response of the two topologically rearranged 20-bit U-shaped strip-based tags for spectral signature-based chipless RFID systems. The space rearrangement of individual tag scatterers in the array reduces the inter-element mutual coupling and thus significantly enhances the frequency and amplitude robustness of their radar cross section (RCS). In comparison to the original arrangement of scatterers, the measurement of tags designed for 2 to 4 GHz frequency band showed a significantly improved homogeneity of the RCS curve which results in a more reliable recognition of coded information.

Index Terms—Chipless radiofrequency identification, radar cross section, scatterer.

I. INTRODUCTION

RFID technology has a broad field of applications in commerce, industry, medicine, science and other areas [1]. Production costs play the crucial role in the applicability of this technology. That is why a significant effort has been devoted to investigation and development of RFID transponders that do not use chips - chipless tags. An important problem in the design of chipless tags is the attainable surface volume density of stored information (in bits per cm²). In this field, RFID chipless tags have been unable to compete with optical barcodes so far. A disadvantage of optical barcodes, however, is the need for direct unscreened contact between the code holder and the reader. In the case of RFID tags, the reader can be screened, since detection is performed by radio waves.

The most widely spread kind of spectral signature-based chipless tags are represented by an array of uniplanar resonant elements – scatterers etched in metalization on a thin dielectric film or printed by a conductive ink on a paper substrate [2, 3]. This array ensures a frequency selective reflection when the tag is illuminated by an incident electromagnetic wave. The bit information “1” or “0” is encoded using the presence or absence of resonance peaks in frequency response of the tag radar cross section (RCS) by insertion or removal of the resonator with corresponding resonance.

Several topologies of frequency-based scatterers have been proposed, among them e.g. C-shaped [4], multiple C-shaped [5, 6] strips, concentric strip rings forming polarization independent tags [7], or other polarization independent tags [8, 9], dual polarized tags [10], tags based on stepped impedance resonators [11] or complementary slots-in-plate [12]. However, the arrangement of scatterers in descending order according to their resonant length suffers from a strong mutual coupling of neighboring elements. The removal of particular elements in order to code a bit words containing ‘0’ bit information significantly affects the frequency stability and magnitude uniformity of resonant peaks in RCS curve of the whole scatterer array; see e.g. [4, 8]. As the received power of potential chipless RFID reader is inversely proportional to the reader-chip distance, we may expect that from a certain distance, the lowest RCS resonant peaks will be unreadable and the reading of overall information may exhibit fatal errors. Given the uniformity of magnitude and frequency interval of individual resonant peaks of RCS curve, the RCS robustness is of the highest importance in chipless RFID technology. The largest and smallest RCS resonance peaks may differ in amplitude level by up to 8 dB [4] or even 13 dB as presented in this study. The mutual coupling can be reduced e.g. by using the modified scatterer topology with inclined arms of U-shaped dipole [13]. However the overall reduction of mean-value of RCS level of the transponder represents the negative accompanying effect of this solution.

This paper proposes a different approach to reduce the mutual coupling between particular resonators by rearrangement of the order of individual scatterers in the array, so that the resonators with neighboring resonant frequencies are placed further apart in a new array. The new tag response considerably improves the frequency and amplitude robustness of RCS response without the mean-value of RCS level being decreased. Thereby the reliability of reading the coded information is significantly enhanced.

II. ARRANGEMENT OF SCATTERERS IN THE CHIPLESS TAG

Fig. 1 depicts photograph of the layout of original and proposed and further referenced 20-bit chipless tag, composed of an array of U-shaped strip scatterers representing a bit word ‘111111111111111111111’. The topology of basic array element is inspired by the one used in [4]. The outer size of
the largest element is $25.5 \times 2.5$ mm, while the dimensions of the smallest one equal $16 \times 2.5$ mm, with the strip width of 1 mm and the gap size equal to 0.5 mm. Consequently, all RCS resonance peaks match the frequency range from 2 to 4 GHz so that the performance of the tag would be comparable with those of presented by Vena [4]. The distance between each two neighboring elements, which are arranged according to the element length from the largest one to the shortest one in descending order, is 1 mm. The tag motif was etched on the low-loss dielectric substrate Rogers RO4003 ($\varepsilon_r = 3.38, \tan \delta = 0.002$) with the thickness of 0.2 mm. The incident excitation field is oriented parallel to the shortening strip stub placed at one end of each scatterer, i.e. horizontally to the tag presented in Fig. 1.

To reduce the mutual coupling between directly adjoining scatterers with neighboring resonance frequencies in order to improve robustness of RCS curve, we have proposed a modification of element arrangement. The scatterers 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. 1(b) and [14]. In this layout, the resonators with neighboring resonance frequencies are then located further apart and thus their coupling is substantially reduced. The third array configuration varies from the second configuration by the alignment of scatterers to the open end (see Fig. 1c, which further increases the distance of shortening strip stubs of neighboring elements).

All three scatterer arrays (i.e. the reference and two with element-rearrangement) were tested for magnitude and frequency interval uniformity of RCS response using configuration of coding the ‘11111111111111111111’ bit word. Polarization of incident electric field is oriented parallel with the short strip stub. Scatterers in positions 6 and 15 (counted from the largest one) are missing; see Fig. 2.

### III. Simulated RCS of Tags

Chipless tags were simulated by MoM software Zeland IE3D, using the infinite dielectric layer implementation with 20 cells per wavelength with narrow edge cells in order to perform a precise modeling of current density distribution in transversal cut of the strip. RCS is calculated by IE3D from the field quantities for plane wave excitation.

Simulated RCS response of 20-bit chipless tags representing a bit words ‘1111111111111111111111’ (thin black line) and ‘11111011111110111111’ (thick red line) is depicted in Fig 3. In case of reference tag; see Fig. 3(a) we may notice that due to removing of 6th and 15th scatterers corresponding resonant peaks are missing. However two lower neighbouring resonant peaks significantly reduced their magnitude and one higher neighbouring peak raised its magnitude. The overall magnitude uniformity is thus deteriorated. The difference between the highest (-30 dBsm) and the lowest (-40 dBsm) RCS magnitude peaks is about 10 dB. Further, we may notice that the nearest lower and higher neighbouring peaks slightly change their resonant frequencies in the direction to the original missing resonance. Thus, both magnitude and frequency interval uniformity of RCS response is worsened.

Furthermore, the lowest and the highest resonant peaks in RCS curve of bit word ‘1111111111111111111111’ are significantly higher and lower, respectively, than the rest of the inner peaks.

On the other hand, both element-rearranged arrays coding a bit word ‘11111011111111011111’ exhibit missing resonances without the effect of distortion of magnitude and frequency interval uniformity of RCS curve; see Fig. 3(b), (c). The difference between the highest (-32 dBsm) and the lowest (-36 dBsm) RCS magnitudes is only about 4 dB.
The element-rearranged configuration with alignment to the short ends exhibits slightly higher magnitude distortion of 16th to 18th resonant peaks. Further, we may notice, that the three lowest resonant peaks of a bit word ‘11111101111111011111’ are about 2-3 dB higher than the rest of the peaks; see Fig. 3(b), (c).

IV. MEASUREMENT

To verify the simulated results, we performed the monostatic measurement of tag RCS performance by R & S ZVA 40 network analyzer in frequency band 2 to 4 GHz in an anechoic chamber; see Fig. 4. It was based on the evaluation of reflection coefficient of a double ridge horn antenna DRH 20 [15] in front of which ascatterer at a distance of 0.3 m was placed. The far field for the horn aperture diagonal of the size 0.1 m is about 0.2 m at 3 GHz \(2D/\lambda_0\) so that the condition for evaluation of RCS by measurement is fulfilled. The calculation of RCS response of the tag was performed by the relation used in [4] and modified so that it was applicable to the one-port case

\[
\sigma_{\text{tag}} = \left( \frac{S_{11}^{\text{tag}} - S_{11}^{\text{iso}}} {S_{11}^{\text{ref}} - S_{11}^{\text{iso}}} \right)^2 \sigma_{\text{ref}}, \tag{1}
\]

where \(S_{11}^{\text{tag}}\) is the reflection coefficient, when the measured tag is used as a scatterer. \(S_{11}^{\text{ref}}\) represents the reflection coefficient, when the reference plate is used as a scatterer. \(S_{11}^{\text{iso}}\) is the reflection coefficient of antenna itself in case that no scatterer is used and comprises the residual reflection from the experimental surroundings. \(\sigma_{\text{ref}}\) is the RCS of the measured tag, \(\sigma_{\text{ref}}\) is the RCS of the reference scatterer, which is the rectangular metal plate 26 x 70 mm\(^2\) in size (corresponding with the measured tags) and 0.3 mm in thickness. Its analytical formula for RCS is as follows:

\[
\sigma_{\text{ref}} = 4\pi a^2b^2 \frac{\lambda^2}{\lambda_0^2}. \tag{2}
\]

The monostatic measurement arrangement enables to avoid the use of angular dependent formula for reference scatterer and eliminates the influence of mutual coupling of the transmitting and receiving antennas in case of bistatic measurement. The measured data are smoothed to suppress the noise caused by a number of residual reflections.

Fig. 3. Simulated RCS response of 20-bit chipless tag composed of an array of the U-shaped strip scatterers representing a bit words ‘11111111111111111111’ and ‘11111101111111011111’ in (a) original alignment to the short ends, and inter-element rearrangement with alignment (b) to the short end, and (c) to the open end.

Fig. 4. Measurement setup using monostatic measurement configuration with detail of the element-rearranged 20-bit tag.

Fig. 5. illustrates the measured RCS response of all three 20-bit chipless tags, original alignment to the short ends, inter-element rearrangement with alignment to the short ends, and to the open ends, representing a bit words ‘11111111111111111111’ and ‘11111101111111011111’.
The two element-rearranged tag configurations provide a comparable uniformity of RCS curve. However, the second configuration aligned to the scatterers’ open ends exhibits a slightly better amplitude and frequency interval of the RCS robustness.

V. CONCLUSION

Two novel element-rearranged 20-bit spectral signature-based chipless tags composed of U-shaped strip scatterers have been investigated. It was proved that such rearrangements significantly improve the uniformity and amplitude robustness of the RCS response which was verified on the tag that encode ‘111110111111011111’ bit word.

Amplitude uniformity and frequency stability of RCS curve is crucial for reliable automated recognition of all bits (presence/absence of resonant peaks) of the tag and extends the reading distance at the given reader sensitivity. This threshold is just limited by level of the lowest peak of RCS curve.

To conclude, it can be claimed that the chipless RFID tags that use the proposed kind of element-arrangement represent promising candidates for reliable recognition of coded information.

REFERENCES


