Platform Tolerant, High Encoding Capacity Dipole Array-Plate Chipless RFID Tags

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ABSTRACT In this paper, we first carry out an in-depth review of the performance parameters of frequency-domain chipless RFID transponders in terms of their spatial density, spectral capacity, and comprehensive encoding capacity (bit/λ^2/GHz) comprising both spatial and spectral performance, and platform tolerance. Secondly, we theoretically and numerically investigate the recently introduced and promising concept of the platform-tolerant chipless RFID transponder based on a detuned dipole array-plate that provides high encoding capacity. We propose, fabricate and measure a 20-bit transponder consisting of an array of 20 detuned dipoles closely coupled to a 60 × 60 mm^2 metallic plate. The radar cross section at the level of −15 dBsm exhibits reliably recognizable minima corresponding to individual dipole resonances. When compared to other published frequency-domain chipless RFID transponders, the encoding capacity reaches 47.4 bit/λ^2/GHz, which constitutes one of the highest values, while achieving a concurrently high level of radar cross section (RCS) reflection response and platform tolerance performance. The measurements confirm very good performance parameters in the cases when the transponder is attached to various packaging materials, such as cardboard, plastic, wood, metal or a human body phantom. The essential benefits of the presented solution include a very good frequency and amplitude stability in the RCS response, which enables a reliable reading of encoded information (if zero bits are coded). The double layer metallization represents an inherent property of the proposed solution, which is a necessary trade-off for high encoding capacity and contemporary platform tolerance.

INDEX TERMS Chipless radiofrequency identification, coding capacity, coupled modes theory, dipole scatterer, electromagnetic band-gap, high impedance surfaces, platform tolerant tag, quality factor, radar cross section.

I. INTRODUCTION

Radiofrequency identification (RFID) is a modern technology, whose utilization has gradually expanding into a wide range of identification, tracking and sensing applications, including the operation of tags attached to lossy dielectric and metallic objects, human bodies, as well as integration of RFID tags with sensors, etc. [1]–[6]. Chipless RFID, using various methods of information storage in passive structures without employing semi-conductor chips (see [7], [8]), represents an emerging and important class of this technology. Chipless RFID encoding methods can be generally divided into two main groups: time domain and frequency domain (or alternatively spectral signature based). To date, the majority of investigated chipless tags include spectral signature chipless tags based on frequency dependent backscattering [9]–[33] of
metallic detuned dipole arrays and other strip-type scattering arrays [10], [12], [16], [17], [22], [23], [32], [33], slotted wideband dipoles [13], slotted plates [11], [28], [29] or multi-band high impedance surfaces [18], [19], [29], [30]. The presence or absence of individual resonant peaks or drops in the tag’s spectral signature represents the logic one or zero, respectively. Moreover, hybrid-coded chipless transponders [34]–[40] have also been developed. They modify more than one parameter of an electromagnetic wave thereby enabling the coding of more than two bits per resonator. Their properties promise a high spatial bit density (yet not always a high encoding capacity as discussed later). Typically, they use an amplitude-phase, amplitude-polarisation coding scheme and independent multi-resonance behavior to enable multiple-bit per resonator encoding. The auspicious emergence of chipless RF identification technology presents a number of challenging issues that have to be addressed. They involve above all the (1) maximization of spectral bit capacity, (2) spatial bit density, and especially (3) comprehensive encoding capacity that integrates both of the previous parameters; see Eqs. (1)-(3) on the next page. Furthermore, we note the importance of frequency and amplitude stability, recognizability of individual resonances of the RCS response for reliable reading at a required distance, and finally the low sensitivity of the tag’s electrical parameters for the cases when they are attached to metallic or dielectric objects located in real-world surroundings [9], [16]. Achieving a desirable platform independence of the tag is a complex problem that represents a major challenge. This is an important design problem that must be addressed before any tag can be used in practical applications. Table 1 depicts the performance comparison of several typical representative examples of previously published frequency domain chipless RFID transponders.

\[
\text{Spectral capacity (bits/GHz)} = \frac{\text{number of bits}}{\text{BW (GHz)}} \\
\text{Spatial density (bits/cm}^2\text{)} = \frac{\text{number of bits}}{\text{size(cm}^2\text{)}} \\
\text{Encoding capacity } \left( \frac{\text{bits}}{\lambda^2 \times \text{GHz}} \right) = \frac{\text{number of bits}}{\text{size } (\lambda^2) \times \text{BW (GHz)}}
\]

The comparison applies relative dimensions of the transponder area (in wavelength-squared) in order to correctly compare tags designed for different bandwidths. In other words, a fair comparison of frequency-domain passive chipless RFID transponders requires frequency rescaling. The majority of the chipless RFID transponder designs that have been reported are based on one-layer printable structures.

Several designs [10], [16], [34], [35], [39], [40] have been reported that reach high spatial density (> 100 bits/\lambda^2) related to relative unit area, while others (10, 16, 26, 29, 40, this work) attain high spectral capacity (> 10 bits/GHz) related to the unit frequency bandwidth. A group similar to the latter one (10, 11, 16, 26, 29, 39, this work) have been shown to exhibit high encoding capacity (> 40 bits/\lambda^2/GHz) in relation to both relative unit area and unit bandwidth. Yet in the case where zero bits are coded, only two designs (namely 21 and this work) provide for the concurrently high encoding capacity (> 40 bit/\lambda^2/GHz), high RCS level (> -20 dBsm) and successful reading reliability verification. Other designs are focused on achieving a polarization independent solution [17]–[22]. However, in most of the presented solutions only tags with unit bit words (111...) were simulated and measured. Consequently, the frequency and amplitude stability of the radar cross section (RCS) response as an essential prerequisite of reliable reading was not verified (see 10, 11, 31 among the group of high encoding capacity designs), was verified negatively (i.e. some resonators were removed in order to encode zero bits), or directly neighboring resonances were distorted in both amplitude and frequency (31). Moreover, the transponders were measured generally in a free space environment and their performance, in the situation where they were placed on real objects, was not tested. The quality and readability of the RCS response and hence also the identification range degradation has to be considered in the case where one-layer solutions are attached not just to metallic or high loss objects, but also to low loss dielectric objects such as wood, cardboard or plastic materials.

Furthermore, electrically small-size array elements provide low values of RCS (typically below −30 dBsm) that implicate a low read range (on the order of tens of decimeters). On the other hand, several works introduced tags based on scattering from larger planar objects, such as wideband slotted or notched dipoles or rectangular plates, where resonant dips in the RCS response curve are ensured by embedded or closely spaced additional resonators, e.g. incorporated slots in a rectangular plate [27]–[29] or concentric rings closely coupled to a metallic plate, forming a high impedance surface (HIS) [31], [32]. Such scatterers benefit from the larger RCS owing to the large electrical size (typically higher than −20 dBsm). In comparison to small-element array-based tags, this implies a larger read range on the order of meters. The concept of sub-wavelength thin absorbing layers called ‘metamaterial absorbers’, inspired mostly by frequency selective surfaces (FSS) [41], is another approach that can lead to planar high bit chipless RFID transponders with independently controlled resonances. Its operational principle and performance are explained by applying either the analytical concept of a surface impedance representation for metallic grids [42], [43] or through full-wave analysis of periodic arrays of resonant unit cells [44], both backed by a conducting plane. Other works describe the performance of single unit cells operating as coupled resonators [45]. An alternative analysis approach involves the application of interference theory for anti-parallel currents flowing on the unit cell and the ground plane [46], which typically employs cavity [47] or transmission line [48] equivalent circuit models. However, most of the thin absorbing layers that have been proposed are only capable of operating in a few bands,
TABLE 1. Performance comparison of frequency domain chipless RFID tags.

| Resonator type [reference] | Frequency range (GHz) | Number of bits | Spatial density (bits/cm²) | Spatial density at center freq. (bits/GHz) | Special capacity (bits/µG) | Encoding capacity (bits/µG/Hz) | RCS (dBsm) | Verification of RCS curve robustness for zero-bit coding | Platform tolerance | Number of metallic layers |
|-----------------------------|-----------------------|---------------|---------------------------|----------------------------------------|-------------------------|-------------------------------|------------|-------------------------------------------------|-----------------|--------------------------|
| **Transponders with linear polarization:** | | | | | | | | | | | |
| C-shaped [10] | 2-4 | 20 | 1.1 | 114.3 | 10.0 | 0.6 | 57.1 | -35 | No | No | 1 |
| Slotted [11] | 4-6 | 4 | 2.4 | 85.2 | 2.0 | 1.2 | 42.0 | -30 | No | No | 0 |
| C-shaped [12] | 2-5 | 3 | 0.3 | 24.5 | 1.7 | 0.1 | 8.2 | -35 | No | No | 1 |
| Slotted [13] | 5-5-17 | 36 | 5.5 | 41.0 | 3.1 | 0.5 | 3.6 | -25 | No | No | 1 |
| C-shaped [14] | 2-5-5 | 9 | 3.0 | 192 | 2.6 | 0.9 | 47.4 | -40 | No | No | 1 |
| Dual-L shaped [15] | 3-7 | 8 | 0.2 | 6.2 | 2.0 | 0.04 | 54.9 | -55 | No | No | 1 |
| C-shaped [16] | 2-2-3.8 | 20 | 1.1 | 112.0 | 12.5 | 0.7 | 70.0 | -35 | Yes | No | 1 |
| **Polarization independent transponders:** | | | | | | | | | | | | |
| Concentric circular rings [17] | 3-1-10 | 19 | 2.1 | 44.3 | 2.8 | 0.3 | 6.4 | -20 | No | No | 1 |
| Octagonal concentric loops [19] | 4-9 | 5 | 1.0 | 21.2 | 1.0 | 0.2 | 4.2 | -15 | Yes | No | 1 |
| Concentric square loops (hybrid) [20] | 8-14 | 18 | 10 | 74.3 | 3.2 | 1.7 | 12.4 | -35 | Yes | No | 1 |
| Concentric circular rings [21] | 6-15 | 8 | 1.1 | 9.2 | 0.9 | 0.1 | 1.5 | -30 | Yes | No | 1 |
| Log-periodic dipole [22] | 2-12 | 7 | 0.3 | 0.5 | 0.7 | 0.01 | 1.8 | -10 | Yes | No | 1 |
| Spiral loaded dipoles [23] | 1.3-3.6 | 20 | 0.7 | 81.6 | 11.1 | 0.4 | 45.3 | -33 | Yes | No | 1 |
| **Waveguide coupled transponders:** | | | | | | | | | | | | |
| Microstrip line + spirals [24] | 3-7 | 35 | 0.6 | 22 | 8.8 | 0.2 | 5.5 | - | No | 2 |
| Coplanar line + spirals [25] | 5-11 | 23 | 0.3 | 4.7 | 3.8 | 0.06 | 0.8 | - | No | No | 1 |
| Microstrip line + L-resonators [26] | 3.5-8 | 8 | 0.7 | 32 | 3.2 | 0.5 | 12.9 | - | No | No | 2 |
| **Slots in plate transponders:** | | | | | | | | | | | | |
| Concentric U-slots in rect. plate [27] | 7-12 | 8 | 9.0 | 89.3 | 1.6 | 1.8 | 17.9 | -35 | Yes | No | 1 |
| Concentric delta slots [28] | 3-10 | 18 | 7.3 | 156 | 2.6 | 1.1 | 22.2 | 22 | Yes (sim.) | No | 1 |
| Series U-slots in rect. plate [29] | 2.2-3.8 | 20 | 0.8 | 76.9 | 12.5 | 0.5 | 48.1 | -17 | Yes | No | 1 |
| **Hybrid coded transponders:** | | | | | | | | | | | | |
| C-shaped, phase-frequency [30] | 2-7 | 23 | 2.9 | 127.2 | 4.6 | 0.6 | 25.4 | -40 | No | No | 1 |
| Concentric U-slots in rect. plate, frequency-polarization [31] | 6-12 | 4 | 9.6 | 106.4 | 0.7 | 1.6 | 17.7 | -35 | Yes | No | 1 |
| Slots in rect. plate, freq.-polarization [32] | 7-13 | 18 | 4.1 | 36.7 | 3.0 | 0.7 | 6.1 | -27 | Yes | No | 1 |
| Dipole and rect. loops, frequency-notch bandwidth [33] | 2-5 | 16 | 0.8 | 58.8 | 5.3 | 0.3 | 19.6 | -15 | Yes | ? | ? |
| Loaded concentric rings, amplitude-frequency [34] | 3-9 | 24 | 2.6 | 65.8 | 4.0 | 0.4 | 11.0 | -20 | Yes | No | 1 |
| L-shaped, frequency-polarization [39] | 6.5 | 10.5 | 18.9 | 236 | 4.5 | 4.7 | 59.0 | -40 | Yes * | No | 1 |

| Platform tolerant transponders: | | | | | | | | | | | | |
| Concentric square loops as HIS [31] | 2-5-7.5 | 5 | 1.3 | 45.0 | 1.0 | 0.3 | 9.0 | -17 | No | PBC | 2 |
| Stepped impedance, harmonic resonances (hybrid) [40] | 3-9 | 79 | 7.9 | 197.5 | 13.2 | 1.3 | 32.9 | -39 | Yes | ? | 2 |
| This work (linear polarization) | 2.2-3.5 | 20 | 0.6 | 61.6 | 15.4 | 0.4 | 47.4 | -15 | Yes | Yes | 2 |

Highlighted rows represent authors’ solutions.
* Negative result of verification, frequency shifts in positions of resonances are demonstrated.

which is a consequence of the limited multi-band behavior of their unit cells [49], [50] or multiple detuned cells [51], [52]. In such cases, the applicable frequency domain chipless RFID transponders are expected to provide at least twenty independently controlled closely spaced resonances, each of them representing one bit of information. Thus, high density, thin, multiple-band, absorption layers having independently controlled stable resonances still pose a major design challenge.

In [32] and [33] the authors introduced a single-layer “RF barcode” dipole structure placed above a large metallic sheet detuned by the dipole width (in line with optical barcodes) and gap of the motif, independently. The 5-bit RF barcodes are evaluated only by means of $S_{21}$ measurements with neither a detailed description of the structure nor the metallic plane size. Thus, an evaluation of comparable properties is not possible.

Indeed, the problem of radiation/absorption of a dipole or patch in close proximity to a lossy dielectric slab on top of a conducting plane is complex and can be rigorously treated only by applying numerical models [53]–[55]. Yet simplified analytical models [42], [43], [46], [47] are still extremely valuable since they provide useful physical insight into the behavior and constraints of the structure.
In this paper, we first analytically investigate quality factors and absorption properties of a single scatterer element of the recently introduced chipless RFID transponder based on an array of detuned dipoles closely coupled to a metallic plate [56]. We apply an analytical approach to study the quality factors and reflection coefficients of a single dipole-plate scatterer placed above a grounded dielectric layer and illuminated by an incident TEM plane wave. The said approach is based on coupled mode theory [57], originally introduced for general resonator terminating waveguides or optical modes, and further applied for analyses of reflect-array elements [58]. The motivation is to find the optimum scatterer size and its height above the plate to ensure a sufficiently deep resonant minima in the RCS response. Moreover, we extensively evaluate the platform tolerance of electrical parameters when tags are attached to various packaging materials, such as cardboard, plastic, wood, metal or a human body phantom. The proposed concept embodies a relatively high RCS response level (about −15 dBsm) and a satisfactory resonance drop depth (2 − 5 dB) of individual removed scatterers (coding zero bits). Compared to the known solutions, the high spectral bit capacity (>15 bit/GHz) together with good performance immunity when situated in close proximity to dielectric and metallic objects represent significant advantages of the presented solution. Very good robustness in the frequency and amplitude stability of the RCS response in the case where zero-bit words are coded, can be considered as an essential benefit for reliable reading. On the other hand, the double layer substrate represents an inherent property and also a disadvantage of the presented structure, which nevertheless might be acceptable in specific applications.

II. THEORETICAL ANALYSIS

In contrast to common antenna applications, in frequency-domain chipless RFID, it is preferable to have the frequency bandwidth of each single tag element as narrow as possible, i.e. a high-quality factor of the element with sufficient value of RCS is required. Both key properties are met in the case of the dipole-array closely coupled to a finite-sized metallic plate, thereby creating a dipole array-plate scatterer [59]; see Fig. 1.

The image principle can be used to simply explain why the quality factor significantly increases at dipole resonant frequencies. The original dipole and image ground plane currents show approximately the same amplitude, yet they possess opposite phases [59] and therefore the field distribution supports energy storage, which increases the value of the quality factor [60]–[63].

A. QUALITY FACTOR AND REFLECTION COEFFICIENT BASED ON COUPLED MODE THEORY

One of the single dipole-plate scatterers from Fig. 1, excited by an incident plane wave, forms a resonant cavity, which is considered to couple to a TM$_{01}$ patch mode (exhibiting conductive and dielectric dissipation losses inside the cavity), and a radiation mode (through which the energy leaks into the form of a propagating wave). According to the theory [59], such a resonator might be treated as a one port device exhibiting a reflection coefficient at the interface of the resonator and the external waveguide/outside space (i.e. at the patch surface reference plane). This can be expressed in the following way:

$$\Gamma(f) = \frac{\frac{1}{Q} - \frac{1}{Q_0} - \frac{2(\beta_0 - k_0)}{f}}{\frac{1}{Q} + \frac{1}{Q_0} + \frac{2(\beta_0 - k_0)}{f}}.$$  (4)

where $Q_t$ is the radiation, i.e. external, quality factor, $Q_0$ represents the unloaded quality factor of the patch cavity, and $f$ is the resonant frequency. The CAD formula for the space wave radiation quality factor was derived by Jackson [64] as:

$$Q_t = \frac{3}{16} \varepsilon_\ell \frac{L_{eff}}{p c} \frac{\lambda_0}{h}.$$  (5)

where $\varepsilon_\ell$ is relative permittivity and $p$ is the ratio of power radiated into space by the patch to the power radiated into space by the equivalent dipole (that has the same dipole moment as the patch). In addition, $c_1$ is a substrate material dependent constant, $L_{eff}$, and $W_{eff}$ represent respectively the effective length and width of the patch, $\lambda_0$ represents the free space wavelength, and $h$ is the dipole height above the metallic plate.

$$p = 1 + \frac{a_2}{10} (kW_{eff})^2 + \frac{3}{560} \left( a_2^2 + 2a_4 \right) (kW_{eff})^4 + \frac{1}{5} c_2 (kL_{eff})^2 + \frac{1}{70} (kW_{eff})^2 (kL_{eff})^2,$$  (6)

where $k$ is the free space wave constant, $a_2 = -0.16605$, $a_4 = 0.00761$, $c_2 = -0.0914153$,

$$c_1 = \frac{1}{n^2} + \frac{2}{5n^4},$$  (7)

and $n = \sqrt{\varepsilon_\ell \mu}$ is the index of refraction of the substrate. The unloaded quality factor $Q_0$ comprises both conductor and dielectric losses of the patch cavity and is given by [59]

$$Q_0 = \frac{Q_c}{Q_c + Q_d},$$  (8)

$$Q_c = \frac{h \omega}{2 \mu_o \sigma},$$  (9)

$$Q_d = \frac{1}{\tan \delta}.$$  (10)

![FIGURE 1. Cross-section (a) and top view of investigated 20-bit chipless RFID transponder formed by 20 detuned dipoles placed above a metallic plate.](image-url)
where $\omega$ is the angular frequency, $\mu$ represents the permeability, $\sigma$ is the conductivity of the metal plates forming the top and bottom cavity walls, and $\tan \delta$ is the loss tangent of the dielectric. The total (i.e., loaded) quality factor $Q_t$ of the cavity comprising all loss phenomena except for the effect of surface waves, which have been found to be negligible (namely by three orders of magnitude lower for the considered air and foam substrates with thicknesses of up to 3 mm) is computed as:

$$\frac{1}{Q_t} = \frac{1}{Q_r} + \frac{1}{Q_c} + \frac{1}{Q_d}$$  \hspace{1cm} (11)

The reflection coefficient at the resonant frequency is derived from (4) as

$$\Gamma (f_r) = \frac{1}{Q_c} - \frac{1}{Q_d}.$$  \hspace{1cm} (12)

It is useful to observe that there are three different conditions for coupling of dissipation and leakage modes:

1) $Q_r > Q_0$, under-coupled,
2) $Q_r < Q_0$, over-coupled,
3) $Q_r = Q_0$, critically-coupled.

Unlike the analysis performed by Karanti in [58], we are interested in the maximum energy absorption of the representative resonator and dipole-plate scatterer, which is achieved for critical coupling. We consider a low loss air and foam substrate with $\tan \delta \sim 10^{-6}$ and $\tan \delta \sim 10^{-3}$. This enables the designer to achieve the highest total quality factor. The metal conductivity is considered to be $\sigma = 4.9 \times 10^7$ S/m. The dipole length is $L = 46$ mm, which is approximately a half-wavelength at $f = 3.2$ GHz in the case of a dipole situated at a height of $h = 1$ mm above the metallic plane. The quality factors of a cavity formed by dipoles with widths of 1 mm and 0.2 mm placed at variable heights above the metallic backplane are depicted in Fig. 2 and 3, respectively.

Obviously, the critical coupling for the dipole of width $w = 1$ mm is attained at a height of $h = 0.7$ mm and $h = 1.2$ mm for the case of an air substrate and foam substrate, respectively. The corresponding radiation quality factors are $Q_{r,\text{air}} = 601$ and $Q_{r,\text{foam}} = 503$, and the total quality factors are equal to $Q_{t,\text{air}} = 300$ and $Q_{t,\text{foam}} = 252$, respectively; see Fig. 2(a) and Fig. 3(a). The critical coupling for a dipole of width $w = 0.2$ mm is achieved at a height of $h = 0.9$ mm and even $h = 1.5$ mm for an air substrate and foam substrate, respectively. The corresponding radiation quality factors attain slightly higher levels of $Q_{r,\text{air}} = 757$ and $Q_{r,\text{foam}} = 540$, with total quality factors equal to $Q_{t,\text{air}} = 382$ and $Q_{t,\text{foam}} = 275$, respectively; see Fig. 2(b) and Fig. 3(b).

It follows that the narrower the dipole width, the higher the total quality factor. However, the effect of narrowing the dipole width intended to increase the total quality factor is less significant if the substrate possesses a higher relative permittivity and is lossy. To see this we compare $Q_{t,1\text{mm}} = 300$ and $Q_{t,0.2\text{mm}} = 382$ in the case of an air substrate with $Q_{t,1\text{mm}} = 252$ and $Q_{t,0.2\text{mm}} = 275$ in the case of a foam substrate.

![FIGURE 2. Quality factors vs. height of a dipole placed on an air substrate above an infinite metallic plane. Dipole size equates to: (a) $46 \times 1$ mm$^2$, and (b) $46 \times 0.2$ mm$^2$. Intersection of the $Q_0$ and $Q_r$ curves correspond to critical coupling according to (42).](image)

Apparently, there is an optimum dipole height for achieving a maximum total quality factor, which is in the range from 0.6 mm to 0.7 mm for both investigated dipole widths placed on the air substrate (Fig. 2). Similarly, the range is from 0.7 mm to 0.9 mm for both widths of dipoles when placed on the foam substrate (Fig. 3). If the dipole height is lower, then it is seen that the total quality factor dramatically drops; see also Fig. 4. In addition, it is worth mentioning that the higher the permittivity and loss of the substrate, the higher the dipole height must be above the metallic plane to achieve critical coupling (i.e. the theoretical point where the reflection coefficient goes to zero).

Comparing the heights of the dipoles for which the $Q_r$ and $Q_0$ curves intersect, we observe: 0.7 mm vs. 1.2 mm for the dipole width $w = 1$ mm; see Fig. 2(a) and Fig. 3(a), and 0.9 mm vs. 1.5 mm for $w = 0.2$ mm; see Fig. 2(b) and Fig. 3(b). Furthermore, the higher the substrate permittivity and loss, the larger the difference between the optimal height required to achieve the maximum total quality factor.
FIGURE 3. Quality factors vs. height of a dipole placed on a foam substrate above an infinite metallic plane. Dipole size equates to: (a) $46 \times 1 \text{ mm}^2$, and (b) $46 \times 0.2 \text{ mm}^2$. Intersection of the $Q_0$ and $Q_r$ curves correspond to critical coupling according to [59].

 FIGURE 4. Total quality factor corresponding to a dipole length of 46 mm as function of dipole width and height above a metallic plane for: (a) an air, and (b) a foam substrate.

The dependence of the reflection coefficient on frequency and dipole height above the metallic plane is depicted in the form of the surface plots in Figs. 5 and 6. As the relative permittivity and loss increase, the value of the reflection coefficient degrades, which constitutes the most significant effect (compare Figs. 5(b) vs. 6(b)). The same effect applies in the case of narrowing the dipole width; compare Figs. 5(a) vs. 5(b) and Figs. 6(a) vs. 6(b).

Therefore, there is a trade-off between: (1) maximization of total quality factor (which minimizes the single scatterer resonance bandwidth and maximizes the overall transponder bit density), (2) minimization of the reflection coefficient (affecting the deep resonant minima of the RCS curve), and (3) the requirement for a low profile and a small surface area of the transponder. When we utilize a low permittivity and a low loss foam-type substrate that enables the support of a thin dielectric substrate with a metallic transponder motif above a metallic plate, the targeted trade-off between the three competing requirements can be achieved using half-wavelength dipole strips of approximately 1 mm in width and placed at a height of approximately 1 mm above a plate. Further reducing either the strip width or its height above the plate degrades either the depth or bandwidth of the resonant minima on the RCS curve; see also Figs. 7 and 8 in Section B.

**B. EM SIMULATION STUDY OF THE RCS OF A DIPOLE CLOSELY COUPLED TO A METALLIC PLATE**

In order to consider metallic losses of a dipole-plate model, we employ the commercial MoM simulator Zeland IE3D to perform parametric studies of a single half-wavelength dipole, which is closely coupled to a metallic plate of $60 \times 60 \text{ mm}^2$; see Figs. 7 to 9. A planar dipole was selected as a reference, which is assumed to operate in free space at a resonant frequency of 3.12 GHz. The length $l$ of the reference dipole is 47 mm, while its width $w$ is 1 mm. It is situated on an air substrate with a relative permittivity $\varepsilon_r = 1$ and thickness $h = 1$ mm (referred to as ‘base size’ in Figs. 7 to 9).
FIGURE 5. Reflection coefficient vs. frequency and dipole height on an air substrate placed above a metallic plane. The dipole size is: (a) $46 \times 1$ mm$^2$, and (b) $46 \times 0.2$ mm$^2$.

As was mentioned above, the aim of the quality chipless RFID transponder design is to reach a high RCS, sufficiently narrow and deep resonance drops and, at the same time, a small overall size. These parameters have an antagonistic effect, so an acceptable trade-off must be found. As it can be seen in Figs. 7 and 8, the depth of the resonance drop is directly proportional to the dipole width and requires a specific value of the substrate thickness (approximately 2 mm for an air substrate).

Therefore, the increase in the dipole width leads to an inconveniently large transponder area. Furthermore, the increase in the substrate height decreases the total quality factor, which in turn results in a wider resonance. Similarly, the increase in ground plane size raises the RCS level and reduces the depth enhancement, while at the expense of a larger structure; see Fig. 9.

The application of a high permittivity substrate, which can minimize the structure thickness, leads to a significant reduction in the depth of the resonance due to the electromagnetic field storage between the dipole and the plate; see Fig. 10.

C. STABILITY ANALYSIS OF RCS RESPONSE DUE TO TOPOLOGY CHANGES IN THE ARRANGEMENT OF DIPOLE SCATTERERS

To analyze the stability of the RCS response due to topological changes in the arrangement of dipole resonators,
a parametric study was conducted of a triplet of detuned half-wavelength dipoles closely coupled to the same metallic plate of 60 × 60 mm²; see Figs. 11 to 12. The dipole triplet selected as a reference structure operates at the resonance frequencies of 3.05 GHz, 3.12 GHz, and 3.19 GHz.

The length of the dipole strips varies from 46 to 48 mm with a length increment Δl reaching 1 mm. Their width attains 1 mm and their transverse distance g is 1.5 mm (it is referred to as ‘base value’ in the figures). Similar to the single dipole analysis, the triplet is situated on an air substrate that is 1 mm thick.

As it was already mentioned, the frequency stability of the resonance drop is the key parameter to gauge the reliability of a bit reading of a transponder. If the mutual coupling of each pair of neighbouring dipoles, determined by their separation distance g, is too strong, then a frequency shift of neighbouring drops can be observed provided that the zero bit is coded in the bit word; see Fig. 11. The removal of a middle resonator in the case where the gap g = 0.3 mm causes a relative frequency shift in the position of the upper resonance drop towards the position of the removed resonator that is approximately equal to 30 % (see Fig. 11c). The acceptability of such a shift for successful tag identification is determined by the threshold parameter settings within the reading procedure.

A similar effect is caused by a length increment that is too small (i.e. a small frequency step). If the middle resonator is removed (in the case where the length increment Δl = 0.2 mm; see Fig. 12c), the frequency shift of the upper resonance decreases to a position somewhere in between the middle and upper resonances. As a result, it becomes impossible to correctly recognize the resonance (bit) that has been removed.

### III. TOPOLOGY OF 20-BIT CHIPLESS RFID TAG

The 20-bit chipless RFID tag is composed of an array of detuned planar dipoles closely coupled to a rectangular metallic plate of size 60 × 60 mm², operating within the frequency range of 2.2 to 3.5 GHz; see Fig. 13. The dipole resonators are located at a distance of approximately 0.01 λ₀ from the metallic plate at the central frequency within the band of interest. Although the respective distance enables sufficient excitation of resonators, the resonators are close enough to increase the quality factor to sufficiently reduce the
impedance bandwidth. The length of dipole strips varies from 37 to 56 mm with a length increment of 1 mm. Their width accounts for 1 mm and their transverse distance is 1.5 mm. The substrate thickness between the dipole array and plate is 1.1 mm. The substrate comprises of Rogers RO4350 and a foam layer. The former has a relative permittivity of $\varepsilon_r = 3.66$, a loss tangent of $\tan \delta = 0.003$ and a thickness of 0.1 mm, while the latter has the relative permittivity of $\varepsilon_r \sim 1.3$, a loss tangent of $\tan \delta \sim 0.02$, and a thickness of 1 mm. These properties help to reduce the effective permittivity and thus deepen the corresponding resonant drops; see Fig. 10.

IV. SIMULATION OF BIT WORD CODING

The chipless tags were simulated by the MoM software Zeland IE3D, using the infinite dielectric layer implementation with 20 cells per wavelength and narrow edge cells to perform a precise modeling of the current density distribution in a transversal cut of the strip. The frequency verification and amplitude stability of the RCS response for the case when the zero bits are coded in the bit word was performed by means of three different 20-bit transponders representing the bit words ‘11111111111111111111’, ‘11110111111111011111’ and ‘01010101010101010101’ according to the configurations indicated in Fig. 15(b) - (d). The very good robustness of the RCS curve was confirmed; see Fig. 14. For arrays with zero bits (Fig. 13(c)-(d)) we may notice that, due to the removal of the 6th and 16th or alternate scatterers, respectively, the corresponding resonant peaks are missing without any effect on magnitude distortion and frequency interval uniformity of the RCS curve; see Fig. 14. Furthermore, the RCS level is relatively high (approximately -15 dBsm), whereas the depths of the resonance drops are about 2 - 5 dB. This is due to the losses of the foam substrate whose scale exceeds the values considered in the theoretical analysis. We verified the influence of different objects attached to the lower part of the transponders only by performing measurements, which can be considered as a proven technique; see Figs. 18 in Section VI.

V. RCS RESPONSE TO A SLANT POLARIZATION AND AN OBLIQUELY INCIDENT INTERROGATING SIGNAL

To predict the degradation of the tag RCS response to slant polarization and an obliquely incident electromagnetic wave, a series of simulated parametric studies were performed; see Fig. 15 to 17.

The polarization slant measured from the dipole axis at the tag surface plane (Fig. 15), the elevation tilt in a plane parallel to the dipole axes (Fig. 16), and in a plane perpendicular to the dipole axes (Fig. 17) were chosen to all be in the range...
of \{0^\circ, 30^\circ, 45^\circ, 60^\circ, 90^\circ\}\. As expected with linearly polarized scatterers, both the polarization slant and the oblique incidence performance deteriorates the RCS performance, but each of them in a different way. In the case of a polarization slant, the depth of the resonance drops decreases with increasing angle and reaches approximately half of the original depth at an angle of 45°. This is due to a shorter projection of the dipole length into the polarization plane when each of the dipoles has an electrically smaller size compared to the metallic plate size. The absolute value of individual drops in the RCS curve in the range of 1.5 to 2.0 dB are still present allowing for correct determination of the individual resonances for the angle considered. On the other hand, increasing the elevation tilt either in a plane parallel or perpendicular to the dipole axes causes a complete reduction in the RCS level while maintaining almost the same original level of the individual drops. In the case of a tilt in a plane parallel to the dipole axes (Fig. 16), the projection of both the dipole lengths and the size of the plate area in the direction of wave arrival are proportionally smaller. In the case of a tilt in a plane perpendicular to the dipole axes (Fig. 17), even the shape of the resonance drops deteriorates especially at higher frequencies, as the situation here is more complicated. The projection into the direction of wave arrival causes the dipoles to appear closer together and, consequently, the wave imparts a relatively small phase shift on each element.

VI. MEASUREMENT

To verify the simulated results and other properties of the presented transponders, we performed monostatic measurements of tag RCS response by utilizing a R&S ZVA 40 network analyzer within the frequency band of 2.2 to 3.6 GHz in an anechoic chamber as well as indoors; see Figs. 18 and 20. The measurements were based on the evaluation of the reflection coefficient of a double ridge horn antenna DRH 20 [69] in front of which a transponder was placed. The far field for a horn aperture diagonal of length 0.1 m is about 0.2 m at 3.5 GHz \((2D^2/\lambda_0)\), meeting the condition required to perform accurate RCS measurements.

![FIGURE 15. Simulated RCS response of a 20-bit tag to a slant polarization of a perpendicular electromagnetic wave in the tag surface plane with the polarization angle serving as a parameter.](image1)

![FIGURE 16. Simulated RCS response of a 20-bit tag to an obliquely incident electromagnetic wave in a plane parallel to the dipole axes with the elevation angle serving as a parameter.](image2)

![FIGURE 17. Simulated RCS response of a 20-bit tag to an obliquely incident electromagnetic wave in a plane perpendicular to the dipole axes with the elevation angle serving as a parameter.](image3)

![FIGURE 18. Measurement setup using monostatic configuration in anechoic chamber with detail of 20-bit tag constituted by dipoles closely coupled to a rectangular plane situated on a wooden plate.](image4)

The calculation of transponder RCS response by means of monostatic measurements was performed according to the following relation [23]:

\[
\sigma_{\text{tag}} = 20 \log \left| \frac{S_{11}^{\text{tag}}}{S_{11}^{\text{ref}} - S_{11}^{\text{iso}}} \right| \sigma_{\text{ref}},
\]

where \(S_{11}^{\text{tag}}\) is the reflection coefficient, provided that the measured tag is used as a scatterer. \(S_{11}^{\text{ref}}\) represents the reflection coefficients, when the reference plate is used as a scatterer. \(S_{11}^{\text{iso}}\) constitutes the reflection coefficient of the antenna itself in the case where no scatterer is used, which takes into
FIGURE 19. Measured RCS response of bit words ‘11111111111111111111’ in comparison to ‘11111011111111101111’ and ‘01010101010101010101’ in (a) free space, and attached to: (b) a cardboard plate, (c) a wooden plate, (d) a plastic plate, (e) an agar human body phantom, (f) a metallic plate.

account the residual reflection from experimental surroundings. $\sigma_{\text{tag}}$ symbolizes the measured tag RCS, $\sigma_{\text{ref}}$ represents the RCS of the reference scatterer, which is a rectangular metal plate of $60 \times 60 \text{mm}^2$ in size (corresponding to the measured tags) and $0.3 \text{ mm}$ in thickness. An analytical formula for the RCS is given as follows:

$$\sigma_{\text{ref}} = 4\pi \frac{a^4}{\lambda^2}. \quad (14)$$

A. MEASUREMENT IN ANECHOIC CHAMBER

The basic set of measurements were performed in an anechoic chamber at a distance of 500 mm from the radiating double ridge horn antenna; see Fig. 18.

In order to guarantee that the transponders were electrically immune to objects situated directly below them, we performed measurements on a rectangular plate of $150 \times 200 \text{ mm}^2$ made of common materials such as cardboard (thickness $t = 6 \text{ mm}$), wood ($t = 5 \text{ mm}$), plastic ($t = 1 \text{ mm}$) and metal ($t = 0.1 \text{ mm}$). Furthermore, we also employed an agar phantom of $120 \times 80 \times 15 \text{ mm}^3$ with $\varepsilon_r \sim 55$ and $\tan \delta \sim 0.5$ representing the influence of a human body. Fig. 19 contains three curves corresponding to the tag configurations from Fig. 13(b) - (d). The solid black line represents the full 20-bit word ‘11111111111111111111’, whereas the dashed red line symbolizes the bit word if two ‘0’ bits are coded, while the dot-and-dashed blue line symbolizes the bit word for the case when every other bit is ‘0’. If low loss materials such as cardboard, wooden and plastic plates are utilized, the radar cross section response shows a similar character as in the free space measurement; see Figs. 19(b) – (d). The employment of a high loss object hinders the resonance drop such that it amounts to 7 - 15 dB, which is advantageous for the measurement and bit word evaluation. In the case where
the transponder situated over the metallic plate is measured, a totally different character of RCS response can be observed; see Fig. 19(f). If an additional metallic plate isolated from the tag ground is used, the resonance drops are transformed into resonance peaks. However, owing to appropriate evaluation criteria, it is still possible to determine the bit information. The radar cross section response embodies strong resonance peaks with magnitudes in the range of 5 to 10 dB. Therefore, an in-depth follow-up analysis is indispensable to better understand this behavior and improve the respective type of transponder so that its reliable operation can be eventually attained for cases when it is attached to metallic objects.

**B. INDOOR MEASUREMENT**

To verify the basic capability of transponder operation outside the anechoic chamber under realistic conditions, indoor measurements were taken for two basic cases indicated in the previous subsection, namely in free space and on the rectangular wooden plate of size $150 \times 200$ mm. In order to improve the signal-to-noise ratio, the distance between the transponder and identical radiating double ridge horn antenna was reduced to 250 mm; see Fig. 20.

In both cases the ripples in the radar cross section response expanded due to the multipath propagation and multiple reflections. Yet given the measuring distance of 250 mm, the depth of the resonance drop was significantly higher than the ripple, so the bit information can be identified; see Figs. 21-22. Furthermore, the drops in the RCS response of a transponder situated over the wooden plate exceed the drops in the free space case. This phenomenon is attributable to the presence of a larger object that, to a certain degree, shadows the multiple reflections from the wall or other objects situated in a straight line behind the measured transponder; see Fig. 22.

**VII. CONCLUSION**

In this paper, a summary and performance evaluation of recent frequency-domain chipless RFID transponders, including hybrid designs, was presented. It was shown that only a few designs exhibit high encoding capacity per both relative unit area and unit frequency band (in bits/$\lambda^2$/GHz). Only the proposed concept of a dipole array coupled to a metallic plate exhibits concurrently: (1) high encoding capacity, (2) platform tolerance of electrical parameters when attached to various dielectric objects, and (3) stability of RCS response for reliable reading when individual scatterers are removed to encode logical zeros.

A platform tolerant 20-bit chipless RFID transponder based on an array of dipoles above a plate was theoretically and numerically investigated for maximization of high encoding capacity and robustness of reading response. Moreover, the resulting design was subsequently manufactured and extensively tested. It exhibited a reliable reading performance in cases when it was attached to various dielectric objects. Only the use of a metallic pad led to a different shape in the RCS response. Although all 20 resonant peaks were apparent, the transponder configuration in question might be considered unreliable for reading purposes. In comparison to other known solutions, the proposed concept shows a high encoding capacity exceeding 47 bit/$\lambda^2$/GHz together with a relatively high RCS response of approximately $-15$ dBsm. In addition, the design is shown to exhibit a satisfactory resonance drop depth ranging from 2 to 5 dB and sufficient platform tolerance of electrical parameters when the tag is attached to various dielectric objects and
the interrogating signal is incident on the tag in a direction perpendicular to its surface. A very good frequency and amplitude stability in the RCS response for the cases when zero bits are coded together with the need for reliable reading suggest that the proposed solution is an ideal candidate for employment in many chipless RFID applications. The double layer metallization represents an inherent property of the proposed solution as well as a necessary trade-off for platform tolerance.

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