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Improvement of HF RFID Tag Detection With a Distributed Diameter Reader Coil

Antoine Diet, Marjorie Grzeskowiak, Yann Le Bihan, Marc Biancheri-Astier, Maati Lahrar, Christophe Conessa, Megdouda Benamara, Gaëlle Lissorgues, and Francisco De Oliveira Alves

Abstract—This letter focuses on 13.56 MHz high-frequency radio frequency identification (RFID) in the case of small tags detection, with an effective area below 1 cm². In such an identification system, based on load modulation principle, the magnetic coupling coefficient k and quality factor of the RFID reader coil are the key parameters. The main goal of this letter is to improve the detection of small tags over a given surface of 10 × 10 cm² by modifying the reader coil structure, and consequently the coupling coefficient k . Several coil designs are compared experimentally by distributing the diameters of their turns among three possible values. The design of the coils is based on empirical formulas that are in good agreement with experimental measurements. Electromagnetic simulations are performed to confirm the magnetic field distribution of the different designs. The results show that distributed diameter coil (DDC) as RFID reader coil is clearly efficient in this context of the RFID detection. The DDC structures determine the k factor, and, as k is low, the quality factor Q is a second parameter that can improve, in a second step, the RFID detection performances in function of the tag position and orientation.

Index Terms—Coil, HF RFID, magnetic coupling, near field.

I. INTRODUCTION

RADIO frequency identification (RFID) is a mature technology for different applications and domains [1], [2] such as animal tracking (125/134 kHz) or contactless cards (13.56 MHz). Other domains are targeted for the traceability of devices whatever their size and environment (presence of water and/or metal for example). RFID system at high frequency (HF) (13.56 MHz) is based on reader and tags coils magnetic coupling for which a tradeoff exists between the maximum range of detection and a minimum bandwidth to permit data exchanges. In this letter, we investigate the difficult case of small HF RFID tags, typically less than 1 cm² of area, compared to the RFID reader coil antenna. The reference surface of investigation of

the reader coil is 10 × 10 cm², implying a surface ratio of 1%, unused in common RFID applications such as smart/vicinity cards that usually present a ratio superior to 10%. The objective is to increase the detection ability of such small tags in a volume of detection, onto the above-mentioned 10 × 10-cm² surface for any possible orientation and position of the tag. This implies, at first glance, an increase of the mutual inductance between the tag and the reader coils. Some works concerning the maximization of the magnetic field at a given point of the space, by distributed turns coils are reference works [1]–[5]. However, our goal is to maximize the volume of detection for any tag orientation (and position) rather than the magnetic field value itself at a given point. This detection ability drives to consider the magnetic field integration on the effective surface of the RFID tag coil.

RFID detection cannot exist without an optimization of the coil quality factor Q . In the case of vicinity cards, where the area ratio is higher than 10%, Q is set around 20, according to a tradeoff between powering range and data bandwidth, providing a data rate transfer up to 150 kb/s [2], [6], [8]. In the case of small tag detection with an area ratio of 1%, the influence of Q is different since we are in a weak magnetic coupling case. It is important to consider several points: 1) The tag is a tuned load. 2) Its Q factor and the mutual inductance between the reader coil and tag coil both determine the bandwidth [2], [6], [8]. 3) The area ratio determines (and limits) the mutual inductance and modifies the influence of the tag Q factor on the impedance seen by the reader. Improving the tag powering by maximization of the value of Q drives to define some fixed positions where the RFID detection can be optimum, but the orientation and position of the tags are not considered in that way. As the detection should be optimized in volume, our priority is to maximize the area of detection for any orientation. Consequently, this value of Q , and its influence on the load-modulation, can be different in function of the coils considered for the reader and the tags.

In this letter, we compare different types of reader coil solutions by distributing the diameter of their turns. The study is based on an empirical formula for circular coils design [9], defined in (1). Our approach is to design a reader coil inside a given area of 10 × 10 cm² to target an optimal size for RFID detection in the range of 5 cm [6]–[8] (vicinity application). Also, the combination of the different diameters is set by integer numbers as it represents turns in the realization; thus, constraining a possible optimization. Three diameters, d_1 , d_2 , and d_3 , were chosen. d_1 is set to 9 cm, to be included in the 10 × 10-cm² surface, d_3 is set to 0.9 cm, corresponding to the range of the tag dimension, and d_2 is set to the rounded mean value of d_1 and d_3 , i.e., 5 cm. Five coils are presented in the next part, based on the

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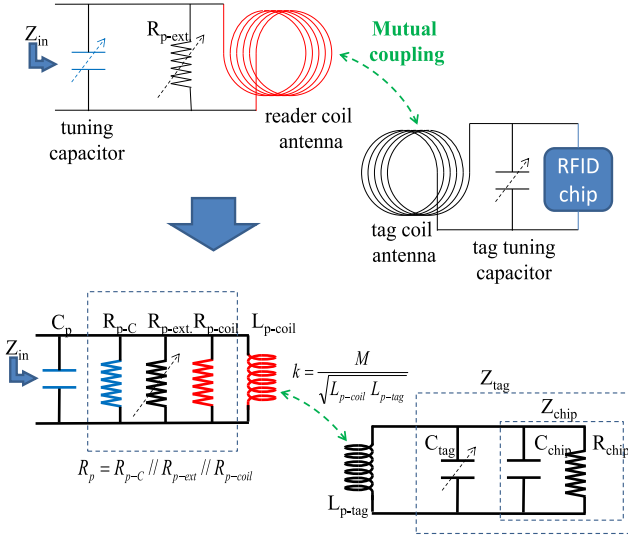


Fig. 1. (top) HF RFID load modulation and (bottom) equivalent circuit.

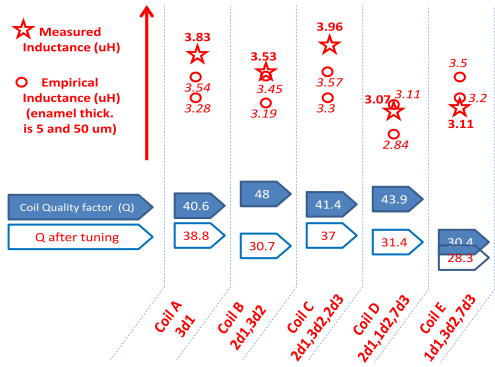


Fig. 2. (top) Different coil measured and empirical inductances. (bottom) Measurements of coil quality factors before and after tuning.

distribution of their diameters among these three values, leading to the concept of distributed diameter coils (DDCs). RFID detection tests are reported and show different performances for the detection of the tag in horizontal and vertical position/mode (referred to as Hm and Vm), as define in Fig. 3. Computer Simulation Technology (CST) simulations confir that some DDC magnetic fiel distribution are fruitful for the detection of small tags (small effective area) in any position and orientation.

II. DDC DESIGN

RFID at HF frequency (13.56 MHz) is based on the load modulation principle in which the magnetic coupling creates a bidirectional physical link between the reader and the tag load impedance. Data are interpreted by the interrogator/reader that detects the envelope variation of the “input” impedance, Z_{in} seen by the reader, in function of the chip impedance variation, Z_{chip} , as represented in Fig. 1

$$Z_{in} = \left[\frac{R_p}{1 + jQ_{reader}} \right] // [jL_p\omega (1 - \delta_{k,\omega} L_{p-tag}, Z_{tag})]$$

$$Q_{reader} = \frac{R_p}{\omega L_{p-coil}} = R_p C_p \omega$$

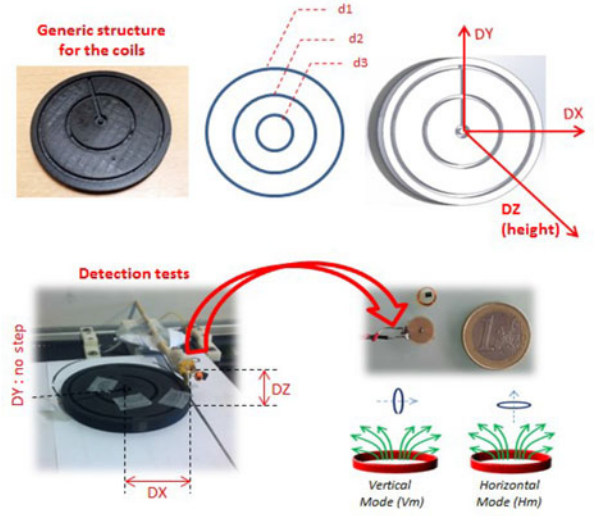


Fig. 3. (top) Experimental setup with DX and DZ variation and 3-D fabricated plastic base. (bottom) Detection test setup and definition of the tag modes, Vm and Hm, and photograph of the small spiral coil for the tag.

$$Z_{tag} = Z_{chip} // \frac{1}{jC_{tag}\omega} = R_{chip} // \left[\frac{1}{j(C_{tag} + C_{chip})\omega} \right]$$

$$\delta_{k,\omega} L_{p-tag} Z_{tag} = \frac{jM^2\omega}{(Z_{tag} + jL_{p-tag}\omega) L_{p-coil}}$$

$$= \frac{jk^2\omega L_{p-tag}}{Z_{tag} + jL_{p-tag}\omega} \quad (1)$$

We expressed in (1) the modulated impedance seen by the reader/interrogator, Z_{in} . As it can be noticed, the expression shows that the magnetic coupling coefficient k is interacting with the tag impedance in the function $\delta(k, \omega L_{p-tag}, Z_{tag})$. The reader coil quality factor Q_{reader} is separately acting on the impedance Z_{in} . Both k and Q_{reader} are the key parameters for improving the RFID communication link. Several structures of reader coils can be tested with some different combinations of k and Q_{reader} . The coupling coefficient k is define exclusively by the geometrical description of the coils, i.e., their shapes, orientation, and relative position. Q_{reader} is determined by the reader coil shape and material, including wire losses. The reader coil geometry define by the design is acting on these two factors at the same time, in a complex manner, and we have to fi some constraints to perform a comparison of the different reader coil solutions.

The design of coils for the HF RFID reader is done with the constraint to get the same self-inductance value L , and the comparisons of detection performances are done at the same quality factor by adding a parallel resistance after tuning (allowing only to decrease Q_{reader}). In that manner, the quantity of magnetic energy generated and the impedance seen by the reader are equivalent in each case. L around $3 \mu\text{H}$ is chosen in order to allow multiple combinations of turns with the abovementioned diameters d_1 , d_2 , and d_3 . As a consequence, the wire lengths of each coil are not equal. The different coils structures are referred to A, B, C, D, and E coils with the description format $x d_1 y d_2 z d_3$, where x , y , and z are integers number representing the numbers of wire turns for the different diameters. According

to (2) from IB Technology [9], the empirical reader coil inductance can be evaluated by summing the three partial inductances obtained from the three different turn diameters, neglecting in a first step the mutual coupling between these three subcoils

$$l_{\text{emp.}}^n H(d_i) = 2\pi d_{\text{coil}_i}^{\text{cm}} \ln(\pi d_{\text{coil}_i}^{\text{cm}} / d_{\text{wire}}^{\text{cm}}) N^{1.9}$$

$$L_{\text{emp.}}^n H_{\text{global}} \approx l_{\text{emp.}}^n H(d_1) + l_{\text{emp.}}^n H(d_2) + l_{\text{emp.}}^n H(d_3). \quad (2)$$

As was highlighted by (1), k and Q_{reader} are the optimization parameters under constraints (i.e., the chosen reader coil and tag coil dimensions), but they are additionally influencing and limiting the detection performance (modulation depth of Z_{in}). By designing the different DDCs in this letter, a different k is defined. A small tag implies a low value of k , and the DDC is a way of improvement for the optimization of k in function of the position and orientation of the tag. The wire lengths, and consequently losses, are different for all the DDCs, implying different intrinsic coil Q factors. We have to compare different cases of Q and k since the influence of Q is linked to k for the RFID detection.

The diameters are set in the fabricated three-dimensional (3-D) printing base, represented in Fig. 3. The enameled copper wire has a diameter of 0.022 cm, and the enamel thickness is known to be around 5–50 μm . This means that the empirical inductance evaluation should integrate a real wire diameter between 0.012 and 0.021 cm, implying an approximation error of several percent. Empirical results are reported in Fig. 2 for these two extreme cases.

In Fig. 2, empirical and measured inductances (with a vector network analyzer) for each coil are compared and show a slight difference (around 10% max.) that can be explained by, mainly, four factors: 1) mutual inductance between subcoils neglected (especially for coil C); 2) fabricated slot width tolerance; 3) enamel thickness uncertainty; and 4) interturn capacitive effects in HF, highly increasing with the subcoils turns number (e.g., D and E coils are supposed to be highly impacted). Q factor ($Q = Q_{\text{reader}}$) is reported in Fig. 2, before and after tuning. The values of Q are also impacted by the interturn capacitive effects in HF and by the wire losses and length that are respectively 84.82 (A), 103.67 (B), 112.16 (C), 92.04 (D), and 95.19 (E) cm. Adding a parallel resistor (only) decreases the value of Q . The comparison of the different structures as potential RFID reader coils, with almost the same values for L and Q , is possible with the experimental setup defined in Fig. 3. In Fig. 3, the lateral displacement axes DX , DY , and the height axis DZ are defined for the RFID tests of detection in Vm and Hm. The center of the tested coil is the origin of the axis. DY will not be used, and only positive values for DX are considered for reasons of symmetry. The 1-cm² spiral tag is shown in Fig. 3.

III. RFID DETECTION TESTS WITH A SMALL TAG

The coils A, B, C, D, and E are tuned at 13.56 MHz with a parallel capacitor, and a variable parallel resistor is added for equalizing the quality factor Q_{reader} . Two different values are set in the detection tests: $Q_{\text{reader}} = 20$ (reference case) and another case defined by $28 < Q_{\text{reader}} < 30$. In this second case, Q_{reader} is 28.25 for coil E since it cannot exceed this value in

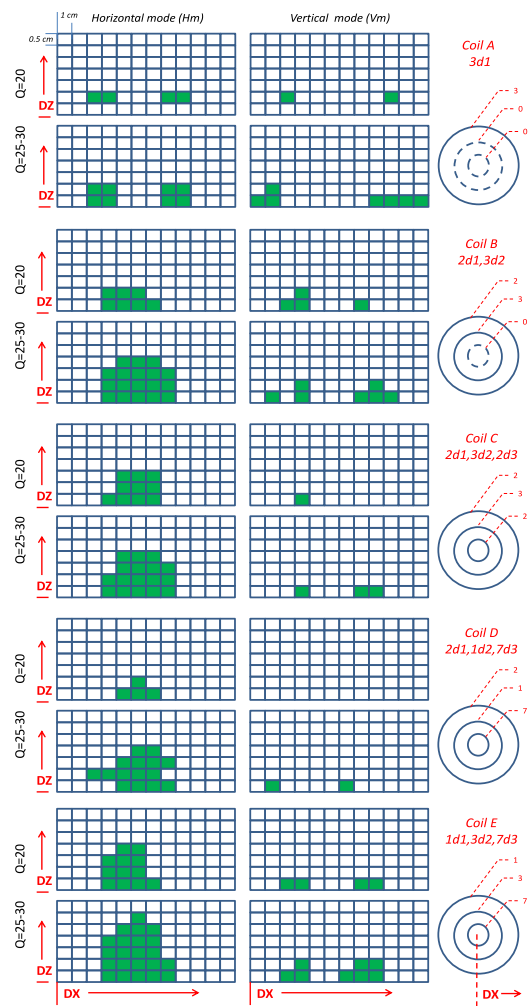


Fig. 4. Results of RFID tag detection in Hm and Vm, for coil A, B, C, D, and E (colored cells), in function of DX (lateral misalignment) and DZ (height). Two values are tested for Q_{reader} : [20] and [25–30].

practice (intrinsic value) and $Q_{\text{reader}} = 30$ for coils A, B, C, and D, which finally drives to a final difference between all the coils Q_{reader} values below 10%. Results of the RFID tag detection (binary values) for coils A, B, C, D, and E, in function of DX and at different DZ , are presented in Fig. 4 for Hm and Vm cases (RFID tag orientation). In Fig. 4, the origin of the graphic (bottom left) is the reference point (0, 0, 0), which corresponds to the center of the tested coil, and the step is 0.5 cm for DZ and 1 cm for DX , due to the size of the tag that limits the spatial resolution. DY is not varied, as previously said (symmetry).

Score bars about colored/detected cells are plotted in Fig. 5 to quantify the improvement due to the variation of Q_{reader} and define a figure of merit for comparison between coils. The two different quality factor values of each coil show an important impact on the detection performances. The increase of Q_{reader} from 20 (left) to a maximum value of 30 when possible (right) improves the detection ability for all coils in Hm and Vm. This increase in Q is possible in our case because the small tag area ratio drives to a k lower than usual applications, such as contactless and vicinity smart cards, implying a different value for $\delta(k, \omega L_{p-\text{tag}}, Z_{\text{tag}})$. Whatever the mode, Vm or Hm, the

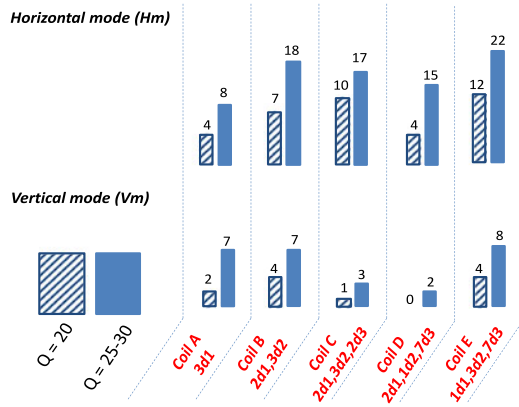


Fig. 5. Score bars of the colored cells for the different coils.

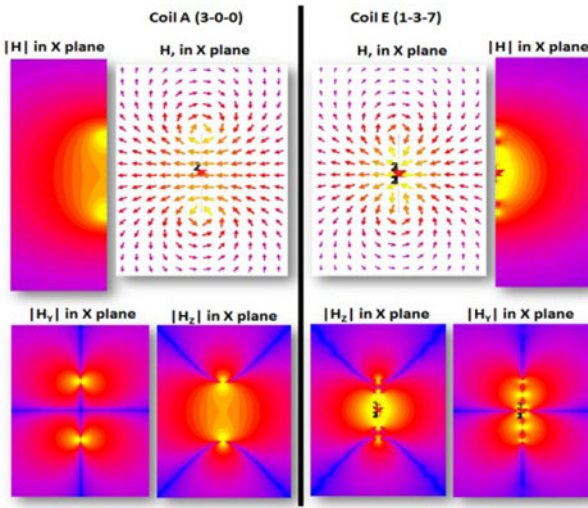


Fig. 6. CST results for (left) coil A and (right) E. (top) H-field magnitude and distribution. (bottom) H-field tangential and normal components.

performances are very different between the coils. Coil E detects the RFID tags more efficiently than the other coils, especially compared to the reference case of coil A that corresponds to a three-turn single-diameter structure.

The DDC E is much more adapted to the case of small tags detection than the coil A since the magnetic field distribution is supposed to provide several positions where the field integration onto the effective tag area is sufficient for powering the tag. This is due to the vectorial modification of the H-field and also to the better repartition of the field strength (flattened shape), as it can be seen in the electromagnetics simulations reported in Fig. 6. Simulations under CST software have been done by modeling the coils by means of three conductive loops (perfect electrical conductor) of diameters corresponding to d_1 , d_2 , and d_3 . A coupling coefficient of 1.7% was evaluated in simulation by a modelization of the coil E and a tag, represented by a coaxial loop of 1 cm diameter, at a distance of 1 cm. A different current intensity can be generated for each loop and corresponds to x , y , or z , as defined in Section II. Consequently, the vectorial field H generated can be compared between the coils. Fig. 6 presents the CST results of H-field generated by the equivalent current distribution for coils A and E. The x -plane is the plane

normal to the x -axis, including the center of the reader coils as the origin. The H-field distribution clearly shows the influence of the DDC structure of coil E in the vicinity of the loops, where the H-field orientation is highly modified compared to the coil A. The magnitude of H-field for the coil E reveals an interesting flattened repartition wider than the two maxima occurring in the case of coil A. In order to qualify the theoretical improvement of RFID tag detection, in Hm and Vm, the normal H_z and, respectively, tangential H_y components of H-field in the x -plane are plotted. Fig. 6 demonstrates that the small tags detection can be favored in the vicinity of the coil E since it presents a more adapted and diversified vectorial orientation (less “holes” than coil A) and a better repartition of the H-field strength (flattened shape).

IV. CONCLUSION

This letter showed an agreement between empirical considerations, simulated results, and experimental tests for DDC structure in HF RFID applications. The interest of such structures is validated by the performances of detection for different configurations, corresponding to different values of k , and at different quality factors Q_{reader} . As the inductance and quality factor were almost identical for the different reader coils, the potential optimization of mutual coupling between a reader coil and the small RFID tag coil is highlighted. According to the score bars of RFID tags detection, coil E is a good example of performance improvement. Complementary simulations point out the coherence of the approach when examining the magnetic field distribution. Perspectives of this letter are: 1) to improve the H-field repartition (vectorial orientation and strength) for different possible diameters; and 2) to formalize a design methodology for improving the detection of RFID tags with a fixed tag coil geometry.

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