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Detection tube for small HF RFID tags, based on mutual coupling with a coil resonator

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Abstract — This communication concerns the detection of 13.56 MHz (HF) RFID “small” tags. Herein, the term “small” refer to an effective area below 1 cm² and the detection principle is in volume, especially inside a tube of 9 cm in diameter and 2m in length. The ability to detect the “small” tags in the tube is achieved by using a coil resonator conformed on the tube surface, following a principle of multiple magnetic coupling, also referred as magnetic field guide. Theoretical considerations on mutual coupling formula and electrical model fit to CST simulations and VNA measurements concerning the evaluation of impedance and coupling factors range. Detection tests with an RFID reader (from IB technology) and NXP SLI-X chip confirm the possibility of detection by providing a first result of 2 cm range. This detection was impossible inside the tube without using the resonator. Perspectives of improvement evocated at the end of the paper are numerous for that structure.

Keywords — RFID; HF; mutual coupling; loop/coil antenna

I. RFID APPLICATION CONTEXT

Radio-Frequency Identification (RFID) is a well-known concept using a mature technology for traceability of objects and persons [1][2]. This technology can involve two main types of radio links: propagation backscattering for UHF (433/868 MHz) or SHF (2.45 GHz) and load modulation thanks to magnetic coupling for HF (13.56 MHz) and LF (125/134 kHz) [1][2].

RFID is used nowadays in a lot of applications, but it still exist some difficult cases in which the technological breakthrough are challenging and for which research and prototyping are still a difficult task. One of such context is, in our case, the traceability of small tags, in the range of 1 cm², [3][4] and especially metallic medical devices (mMDs). The term “small” refer to the size (ergonomic constraint) of the mMDs and the size of the RFID reader antenna/loop. MMDs are used at the hospital where the radio link of UHF RFID is difficult to deploy due to the presence of metal and many others communication systems. We investigated magnetic coupling solutions for that reason because HF and LF are less sensitive to the metal (magnetic coupling phenomenon) and are

in a frequency band lower than communications systems (GPS, GSM, 3/4G, WiFi) and ISM (2.4/5GHz). Some low-cost LF prototypes were tested [5][6] and the conclusion is that it is possible to use this technology but the penalty is the very high number of turns needed for realizing loops antennas for a sufficient reactance value. In this paper, we focused on the HF magnetic coupling solution and, for the prototypes, use the 13.56 MHz ICODE SLI-X long-range chips from NXP with a RFID reader from IB Technology.

Our goal is, more precisely, to detect mMDs with a minimum of manipulation by the hospital technical staff. The tag has also to be of minimum size, below 1 cm² for ergonomic considerations, and the control of tagged mMDs should be automatized. If possible, multiple detections ability is preferred. Consequently, we investigated the principle of detection in volume, for the tagged mMDs, driving us to consider a case study of magnetic coupling where the sizes of the tag and reader loops are very different [5][6][7]. Such problematic is presented in Figure 1 with additional consideration about tag orientations. Our work corresponds to a focus on case 2 and 3.

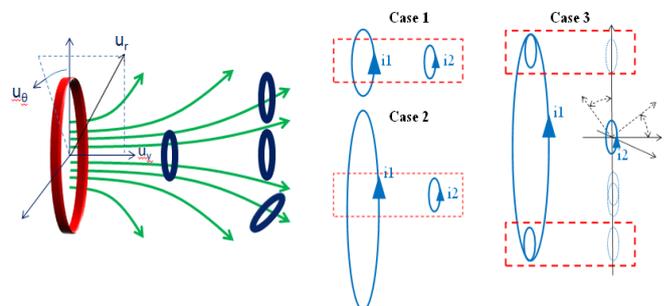


Figure 1 : Magnetic coupling cases study. Orientation and dimension of the secondary loop (usually the tag) drives to difficult and weak magnetic coupling (i. e. cases 2 and 3)

The coupling phenomenon studied is based on the Neumann formula and drives to equation (1), where E and K are elliptical Bessel integrals of first and second kinds, R₁ and R₂ the radii of the two (coaxial) coils, d the distance between the coils and μ_0 the vacuum permeability:

$$M = \frac{\mu_0}{4\pi} \oint_{\Gamma_1} \oint_{\Gamma_2} \frac{d\vec{l}_1 \cdot d\vec{l}_2}{r_{12}} = -\mu_0 \sqrt{R_1 R_2} \left[\left(\rho - \frac{2}{\rho} \right) K(\rho) + \frac{2}{\rho} E(\rho) \right]$$

$$= \mu_0 \sqrt{R_1 R_2} X(\rho) \quad \text{with} \quad \rho = \frac{2\sqrt{R_1 R_2}}{\sqrt{(R_1 + R_2)^2 + d^2}} \leq 1 \quad (1)$$

It is possible to study the optimum size of the reader loop for maximizing the value of M , at different distances between the two loops. In Figure 2, these results are plotted for a coaxial configuration and show a shifting of the maximum value of M in function of the reader loop size (area) and the distance. Also, the value of M is highly decreasing with the distance and can be the reason of a non RFID tag detection if the limit for powering the chip is below the possible values for M .

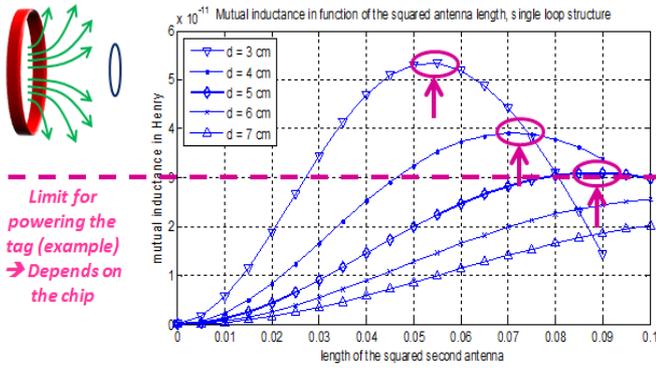


Figure 2 : Theoretical computing of “M” for a loop of 1 cm diameter and a reader loop whose area increases. Curves show a shifting of the maximum for “M” in function of the distance.

To counter this decrease in the mutual coupling effect, the case 3 in Figure 1 expressed the geometrical consideration of multiple loops possibilities. As studied in the literature and in past works at LF [5][12], the geometrical criterion is highly efficient for magnetic coupling increasing if the reader loop/coil structure is optimized and more complex. In HF, the principle of “magnetic-field-guide” is preferred due to the electrical imperfections added by the connections (parasitic capacitance especially). This corresponds to study a multiple magnetic coupling whose parameters are dedicated to the maximization of RFID detection. A resonator will be used in order to relay the magnetic field from the reader loop to the tag loop. The transfer function will be globally maximized for power transfer (high quality factor Q) and also will present sufficient bandwidth for RF Identification (low Q) as it is usually the case in RFID (Q in the range of 20 to 40) [1][2][8][5].

II. MUTUAL COUPLING WITH A RESONATOR

The operation principle can be theoretically schematized by the electrical circuit in Figure 3. The volume detection is performed by inserting mMDs in a tube (2 m long, 9 cm in diameter) for the control. This tube has an encircling loop along its length and its diameter and a resonator is added on the tube surface. We use a copper foil with 100 μm thickness and 6 mm width and the resonator has 2 turns and a square loop/coil

shape of dimension 6x6 cm². In Figure 3, the tube reader/interrogator loop is the inductance L_{ant} at the port 1, the resonator is the port 2 in which the loop/coil L_{res} is loaded by a capacitance C_{res} (Q factor represented by R_{res}) and the RFID tag the port 3, made of a tag loop/coil L_{tag} loaded by the RFID chip ($R_{\text{chip}} // C_{\text{chip}}$). As the electrical elements are all passive, the system is reciprocal: $M_{12}=M_{21}=M_a$, $M_{32}=M_{23}=M_b$ and $M_{13}=M_{31}$. Moreover, the difference of size between the reader loop and the tag loop drives us to consider that the $M_{13/31}$ mutual coupling is quasi-null, at the origin of the problem for which adding a resonator is the proposed solution in this work.

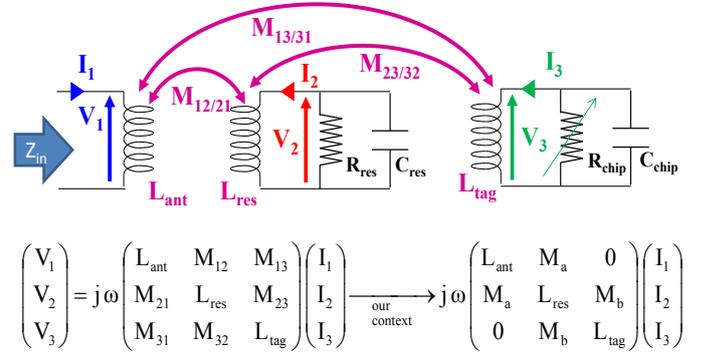


Figure 3 : Principle of mutual coupling between the reader “tube loop”, the coil resonator and the small tag. Harmonic equations are simplified in our context due to electrical reciprocity (passive) and $M_{13} = M_{31} = 0$ (due to the difference in loops sizes).

This schematic is in good agreement with our prototype, as is reported in Figure 4 where the size of the reader loop and the tag can be observed. Also, the simulation performed with CST shows the magnetic field strength around the resonator when the reader loop (tube loop/coil) is fed by its port. The CST simulation gives a theoretical value of $L_{\text{ant, CST}} = 3.1 \mu\text{H}$ for a tube of 2 meters length. Photography of the prototype and the RFID (NXP SLI-X) circular tags used in the next part (test of detection) is shown in Figure 4 (top right).

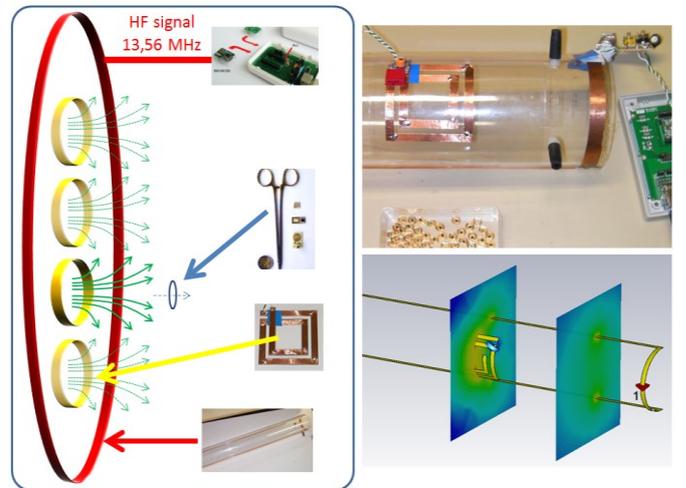


Figure 4: RFID tags and the detection tube (top right), prototype principle and description (left) in agreement Figure 3. CST simulation (bottom right) of the magnetic field magnitude.

Ports 2 and 3 are loaded by “RC” impedances driving to:

$$\begin{aligned} V_2 &= -\left(R_{\text{res}} // \frac{1}{jC_{\text{res}}\omega}\right) I_2 = -Z_{\text{RC}} I_2 \\ V_3 &= -\left(R_{\text{chip}} // \frac{1}{jC_{\text{chip}}\omega}\right) I_3 = -Z_{\text{chip}} I_3 \end{aligned} \quad (2)$$

For RFID detection, it is important to consider the load variation seen by the reader (principle of the load modulation) expressed by equation (3)

$$\begin{aligned} Z_{\text{in}} &= \frac{V_1}{I_1} = j\omega L_{\text{ant}} + j\omega M_a \beta = j\omega L_{\text{ant}} + dZ \\ \beta &= -\frac{j\omega M_a}{Z_{\text{RC}} + j\omega(L_{\text{res}} + M_b \alpha)} \\ \alpha &= -\frac{j\omega M_b}{Z_{\text{chip}} + j\omega L_{\text{tag}}} \\ M_a &= k_a \sqrt{L_{\text{ant}} L_{\text{res}}} \\ M_b &= k_b \sqrt{L_{\text{tag}} L_{\text{res}}} \end{aligned} \quad (3)$$

In order to maximize the detection performance, the variation dZ of Z_{in} in equation (3) induced by the load variation (Z_{chip}) has to be maximized at the resonance frequency. The two-states AM modulation (load modulation principle, ideally ON/OFF keying modulation) is used in this standard. This implies dZ to present ideally a maximal resistive variation with no reactive part. Any reactive part acts as a mistuning of the resonance at the reader port. To reduce this penalty, the overall Q factor has not to be maximal because it increases the electrical sensitivity. This effect is also increased with strong coupling (M_a and M_b high).

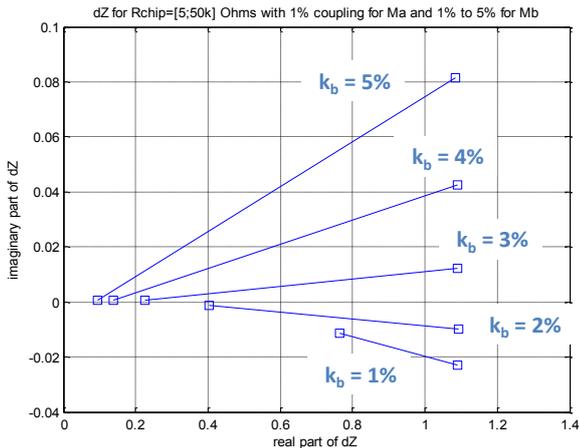


Figure 5: dZ values computed with MATLAB for realistic values of $L_{\text{int}} = 3$ uH, $L_{\text{res}} = 0.2$ uH ($Q_{\text{res}} = 40$). The resonator coupling factor with reader loop is 1%. R_{chip} is varied from 5 to 50k Ohms (load modulation) and the coupling factor between the tag loop/coil and the resonator is from 1% to 5%.

In our context, mutual coupling are weak due to the difference in size between the considered loops/coils. Preliminary observations drive us to consider coupling factor k_a , see (3), of 1% in the case of M_a and to evaluate a coupling

factor k_b , see (3), between 1% and 5% for M_b when the tag is near the resonator. A computation under MATLAB is done in order to evaluate the dZ with our realistic values ($L_{\text{int}} = 3$ uH + a resonator with $L_{\text{res}} = 0.2$ uH and a quality factor $Q_{\text{res}} = 40$) and is reported in Figure 5. As it can be seen in Figure 5, the real part variation (resistive load) is weak but in a sufficient range of 1Ω with our parameters. Moreover, a slight mistuning due to the imaginary part variation (reactive load) is observed in function of the coupling between the tag and the resonator, which can affect the load variation seen by the reader in AM mode.

Next part will report the loops/coils prototype measurements with the VNA (S and Z parameters) and the RFID detection test with the reader and real small tags.

III. TESTS OF DETECTION AND MEASUREMENTS

The prototype is built thanks to a Plexiglas tube of 2 m length with a diameter of 9 cm and a thickness of 2 mm. This material is magnetically transparent at 13.56 MHz. The copper used is the copper foil above mentioned (6 mm width / 100 μm) and the resonator is based on a 2 turns square (6x6 cm^2) loop/coil with 4 mm inter-turns, as seen in Figure 6 (top left). The measured impedance of the 6x6 cm^2 loop/coil is $0.23 + j24 \Omega$, i.e. 285 nH, as seen in Figure 6 (top right).

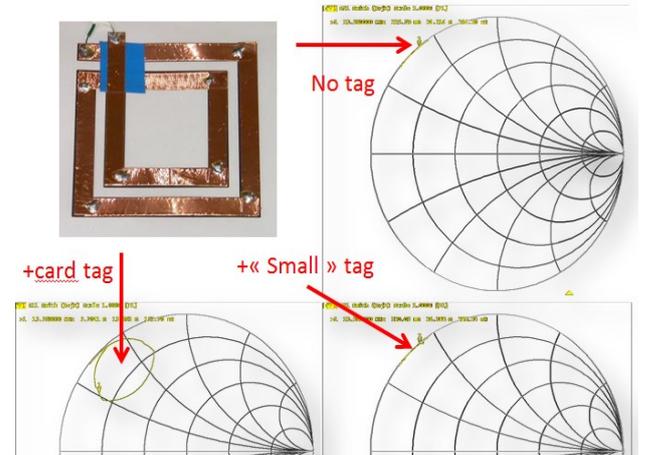


Figure 6: Loop/coil made with copper foil and evolution of the measured impedance in the presence (below 1cm distance) of card and small (circular, 1cm diameter) HF RFID SLI-X tags

In the presence (1 cm distance) of an RFID SLI-X card tag (ISO standard) the coupling is strong and the impedance is highly affected (bottom left in Figure 6). To the contrary, the RFID SLI-X circular tags (below 1 cm of diameter) seen in Figure 4, weakly affect the impedance measured by the VNA, as reported in Figure 6 (bottom right).

We measured the impedance of the resonator in presence of the tag coil unloaded (without the chip) and shortened in order to evaluate experimentally the coupling coefficient k_b . This gives $Z_{\text{coil-tag-unloaded}} = 0.1986 + j 21.939$ and $Z_{\text{coil-tag-shortened}} = 0.1987 + j21.866$, and drives us to evaluate M_b around 73 nH

and k_b around 5.76%. In the same manner, we evaluate k_a with the resonator coil impedance measurement when the tube loop is unloaded and shortened. This gives $Z_{\text{coil-tubeloop-unloaded}} = 0.1885 + j22.256$ and $Z_{\text{coil-tubeloop-shortened}} = 0.184 + j22.236$, and drives us to evaluate M_a around 27.9 nH and k_a around 2.9%. M_{13} was not evaluated in that manner due to the too high level of noise on the measurement, corresponding to the hypothesis of a too weak and neglectable value.

The resonance at 13.56 MHz is achieved with parallel capacitors (560 pF + variable 5/50 pF) and the measured Q_{res} factor is 45.2. The tube is the support of a single turn loop (and same copper foil) whose measured impedance with the VNA is $7+j240 \Omega$, i.e. 3,17 μH , in good agreement with the CST simulation. These steps (and the following ones) are reported in Figure 7.

When the resonator is fixed on the tube, the measured impedance is $13+j273 \Omega$, i.e. 3.2 μH . A parallel capacitor was used for tuning and variable resistance for reducing the global Q factor in the range of 30-40, see the impedance magnitude (dB) in Figure 7. It is important because the tuned tube, with the resonator fixed on it, was connected to the RFID reader as an external RFID antenna.

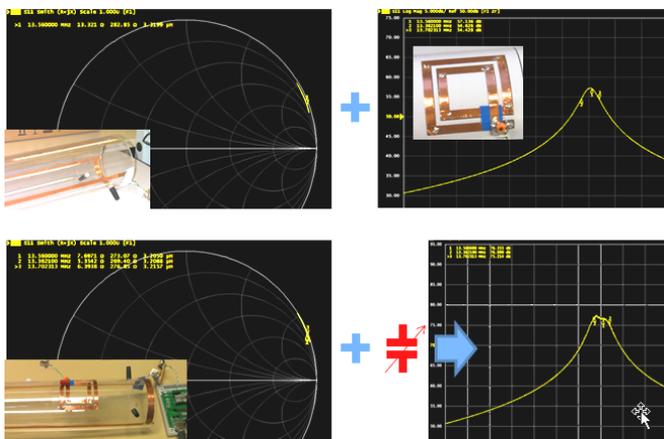


Figure 7: Evolution of the prototype and its measured impedance (VNA measurements), from single reader loop on the tube (top left) towards the addition of the resonator (top right) and its tuning (bottom left and right)

Once the RFID reader is connected to the detection tube carrying its resonator, the small (below 1 cm^2) circular tags used for our tests were detected at a distance below 2 cm from the resonator. These same tags were not detected at all without the resonators. As mMDS will go through the tube, the detection performances are encouraging and illustrate the potentiality of this original structure.

IV. CONCLUSION

In this paper, the work illustrates the potentiality of using coupled resonator for creating a magnetic field guide whose consequence is to enable a complex multiple mutual coupling between several small RFID tags, a resonator and the RFID

reader/interrogator at 13.56 MHz. After theoretical consideration and CST numerical simulations, results of our first prototypes show that it is possible to detect some HF RFID tags whose effective area is below 1 cm^2 . The potentiality of this structure is clearly encouraging because the tags are finally detected inside the tube at a distance of 2 cm from the resonator conformed on the tube surface. The focused application concerns metallic medical devices detection in hospital environment. Perspectives of this work, already in progress, are to study the impact of the different resonator parameters (geometry, turns, Q_{res} ,...) in order to improve the detection performances.

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