Simplified design approach of rectangular spiral antenna for UHF RFID tag

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Abstract: In this paper we present a method to simplify the calculation of spiral antennas for RFID tag settings without resorting to numerical analysis methods. It saves up to 99% of the time required by the simulation based on the method of moments. Thus we present a theoretical and experimental study for the design of the spiral antennas for RFID label in the UHF band. We present in this study the S11 parameter that enables us to evaluate the evolution of current distribution and therefore the resonance frequency of the spiral antennas. This parameter is calculated theoretically by applying the method of moments to wired antenna formed by the rectangular copper spiral printed on a dielectric substrate. The experimental validation of our theoretical models is performed using a network analyzer. The confrontation theory-experience allows us to draw some interesting conclusions concerning the number of loops of the spiral and the choice of dielectric substrate.

Key-Words: Antennas, Spiral antennas, RFID tags, UHF RFID tags, Method of moments, S11 parameter.

1. Introduction
During these last decades, the technologies of information and communications (ICT) have known unprecedented development. The identification technologies are part of these information technologies. Due to the recent development of microelectronics and wireless systems, new contactless identification technologies have emerged: the radio identification technology (or RFID for Radio-Frequency IDentification). These new technologies, by their greater flexibility, make the exchange of information much faster and efficient.

RFID is a technology to recognize or identify with greater or lesser distance (contact tens of meters) in a minimum of time, an object, an animal or a person with an electronic tag. We can cite, for example, contactless smartcard systems, highway tolls without stopping, parking or building access control, etc. ...

It falls into the category of automatic identification technologies (AIDC, Automatic Identification and Data Capture), as the bar code character recognition, pattern recognition, or magnetic cards.

RFID systems use mainly four frequency bands [1], [2] and [3]: 125KHz (LF band, Low Frequency), 13.56 MHz (HF, High Frequency), 860-960MHz (UHF, Ultra High frequencies), 2.45 GHz (microwave). In recent years a growing interest in the field of industry and research focused on passive UHF RFID technology. It presents a low cost solution. It also helps to have a data rate higher (around 20 kbit / s) and achieve a reading range greater than other technologies called passive RFID. This interest has helped put in place in most parts of the world regulations and industry standards for market development of this technology.

In the first part of this document, a brief presentation of passive RFID technology is exposed. Then the modeling of a rectangular spiral RFID antenna using the moment method and the results of simulations and measurements are discussed and presented in a second part. Then we develop a method for estimating the peak current and thus the resonant frequency of spiral antennas.
2. The principle of passive RFID technology

An automatic identification application RFID, as shown in Fig. 1, consists of a base station that transmits a signal at a frequency determined to one or more RFID tags within its field of inquiry. When the tags are "awakened" by the base station, a dialogue is established according to a predefined communication protocol, and data are exchanged.

![Fig.1: Schematic illustration of an RFID system](image)

The tags are also called a transponder or tag, and consist of a microchip associated with an antenna. It is an equipment for receiving an interrogator radio signal and immediately return via radio and the information stored in the chip, such as the unique identification of a product.

Depending on the operating frequency of the coupling between the antenna of the base station and the tag may be an inductive coupling (transformer principle) or radiative (far-field operation). In both cases of coupling, the chip will be powered by a portion of the energy radiated by the base station.

To transmit the information it contains, it will create an amplitude modulation or phase modulation on the carrier frequency. The player receives this information and converts them into binary (0 or 1). In the sense reader to tag, the operation is symmetric, the reader transmits information by modulating the carrier. The modulations are analyzed by the chip and digitized.


To predict the resonant frequencies of the currents induced in the antenna structures forming tags, such as spiral antennas rectangular ICs, we have used initially the model based on the theory of diffraction by thin wires [4]. We arrive at an integro-differential equation, and whose resolution is based on the method of moments [5]. Although a very good result is obtained, the computation time required is a major drawback. It is quite high. In a second step, the study is to find a method to simplify the estimation of the resonance frequency of rectangular spiral antennas in various frequency ranges.

3.1 Method of Moments

It is an integral analysis method used to reduce a functional relationship in a matrix relationship which can be solved by conventional techniques. It allows a systematic study and can adapt to very complex geometric shapes.

This method is more rigorous and involves a more complicated formalism leading to heavy digital development. It applies in cases where the antenna can be decomposed into one or several environments: the electromagnetic field can then be expressed as an integral surface. It implicitly takes into account all modes of radiation.

Moreover, the decomposition of surface current to basis functions, greatly simplifies the solution of integral equations which makes the method simple to implement.

This procedure is based on the following four steps:

- Derivation of integral equation.
- Conversion of the integral equation into a matrix equation.
- Evaluation of the matrix system.
- And solving the matrix equation.

3.2 Formulation of the method of moments [5] [6]

We have chosen the configuration shown in Figure 2, a rectangular metal track, printed on an isolating substrate. It consists of length A, width B and thickness e.

![Fig.2: Dimensions of the track used in the simulation](image)

The theory of antennas for connecting the induced current in the metal track to the incident electromagnetic field (Ei, Hi) using integro-differential equation as follows:
\[
\tilde{t}(l)\tilde{E}^\prime(l) = j \omega \mu \int_0^l I(l') \tilde{r}(l')G(R)dl \\
+ \frac{j}{2\omega} \tilde{r}(l) \text{grad} \int_0^l \tilde{r}(l') \text{grad} I(l')G(R)dl'
\]  
(1)

The method used to solve such equations is the method of moments [4].

The problem thus is reduced to solving a linear system of the form:

\[
[V] = [Z_{mn}] [I]
\]  
(2)

With:

- \([I]\) representing the currents on each element of the structure.
- \([V.]\) representing the basic tension across each element \(m\) in length \(\Delta\) given by:
  \[
  V_m = E_i (m) \Delta
  \]  
(3)

- \([Z_{mn}]\) represents the generalized impedance matrix, reflecting the EM coupling between the different elements of the antenna.

The rectangular loop will be discretized into \(N\) identical segments of length \(\Delta\):

\[
\Delta = \frac{2(A + B)}{N}
\]  
(4)

The discretization step is chosen so as to ensure the convergence of the method of moments.

\[
\Delta = \frac{\lambda}{20}
\]  
(5)

We conclude from this relationship that the number of segments required for convergence of numerical results is:

\[
N = 40 \frac{(A + B)}{\lambda}
\]  
(6)

\(\lambda\) : Represents the smallest wavelength of EM field incident.

The simulations will focus on frequencies between:

- \(100\text{MHz} < f < 1.8\text{GHz}\) whether \(17\text{cm} < \lambda < 3\text{m}\)

The number of segments will be: \(N = 76\). The illumination of the loop is done by an plane EM wave, arriving in tangential impact such that the incident electric field \(E_z\) is parallel to the longest track.

The amplitude of the incident field is normalized \(1\text{V/m}\). we are interested in a loop short-circuited to highlight the resonance phenomena relating to the geometric characteristics of the loop.

We note on the fig.3 the presence of two very distinct zones. A first area in which the induced current remains virtually constant. It corresponds to frequencies whose wavelength is greater than about twice the perimeter of the loop.

Beyond these frequencies we observe the appearance of current peaks, showing that the rectangular loop resonates.

To locate the resonance frequencies of the loop, we use the theory of transmission lines (TTL), moderately few adjustments. The induced current \(I(z)\) on the track IC has illuminated by a plane wave can be expressed by [4]:

\[
I(z) = A_c \sin \left[k \left(\frac{A + B}{2} - |z|\right)\right] + A_d \cos \left[k \left(\frac{A + B}{2} - |z|\right)\right]
\]  
(7)

With:

- \(A_c\): The amplitude of common mode current.
- \(A_d\): The amplitude of the differential mode current.

\(k = \omega \sqrt{\varepsilon \mu} \): wave Vector.

Indeed, \(A_c\) and \(A_d\) can be written as:

\[
A_c = \frac{e_c(0)}{Z_0 \cos \left(\frac{k(A + B)}{2}\right)}
\]  
(8)

\[
A_d = -\frac{e_d(0)}{Z_0 \sin \left(\frac{k(A + B)}{2}\right)}
\]  
(9)

with \(Z_0\) is the characteristic impedance of a transmission line.

\(e_c(0)\) and \(e_d(0)\) : respectively represent the equivalent electromotive forces at the center of the tracks of common and differential modes.

The coefficients \(A_c\) and \(A_d\) take an infinite value only if:

\[
Z_0 \cos \left(\frac{k(A + B)}{2}\right) = 0
\]  
(10)

and

\[
Z_0 \sin \left(\frac{k(A + B)}{2}\right) = 0
\]  
(11)
for $Z_0 \cos \left( \frac{kA+B}{2} \right) = 0$  

$$\cos \left( \frac{kA+B}{2} \right) = 0 \quad (12)$$

$$\Rightarrow k \frac{A+B}{2} = (2N + 1) \frac{\pi}{2} \quad (13)$$

with $N = 0, 1, 2, \ldots \ldots$

$k = \omega \sqrt{\varepsilon_r \mu_r}$. We have considered the isolated loop, surrounded by air, so $\varepsilon_r = 1$ and $k = \omega \sqrt{\varepsilon_0 \mu_0}$

(13) becomes:  

$$\frac{2\pi f \omega}{c} \frac{A+B}{2} = (2N + 1) \frac{\pi}{2} \quad (14)$$

Hence the resonant frequency common mode:

$$F_{Re} = (2N + 1) \frac{c}{2(A+B)}$$

4.2 Measures and results

The coefficient of reflection of antennas made, were measured with a vector network analyzer HP-type operating in the 100Hz-6000MHz band (Fig. 5).

$$F_{Re} = (2N + 1) \frac{c}{2(A+B)}$$

$$\Rightarrow for Z_0 \sin \left( \frac{kA+B}{2} \right) = 0$$

$$\sin \left( \frac{kA+B}{2} \right) = 0$$

$$\Rightarrow k \frac{A+B}{2} = N, \pi \quad (17)$$

With $N = 1, 2, 3, \ldots \ldots$

(17) Becomes:

$$\frac{2\pi f \omega}{c} \frac{A+B}{2} = N, \pi \quad (18)$$

Therefore the resonant frequency of the differential mode is:

$$F_{Rd} = N \frac{c}{(A+B)} = 2N \frac{c}{2(A+B)} \quad (19)$$

We therefore find the result observed in fig.3, which was obtained by the method of moments.

The resonance frequency of the loop can be easily linked to the length $A$ and width $B$ of the loop by the following approximate relation:

$$F_R = N \frac{c}{2(A+B)} \quad (20)$$

With $c = 3108$ m / s, speed of EM waves in vacuum and $N = 1, 2, 3, \ldots \ldots$

4. Simulations and measurements

The simulations were done under the MATLAB environment. The experimental validation was performed at the Laboratory LTPI / RUCI in Fez.

4.1 Achievement

We have made various prototypes of antennas as shown in Fig.4, using as the substrate, glass epoxy, type FR4 with relative permittivity $\varepsilon_r = 4.32$ and 1.53 mm thick.

![Fig.4: Antenna loops made](image)

5. Evaluation of peaks and frequency of resonance of induced currents in function of geometric characteristics of printed loop

The assessment of the size and position of resonance peaks of currents distributed on the printed tracks is crucial for designers of antennas tags. Indeed the action of these peaks can completely change the normal operation of the transponder.

In this part the evolution of the amplitude of these peaks and their resonance frequency will be studied in function of geometric characteristics of loops.

5.1 Evaluation of the peaks as a function of the perimeter of the printed loop and the report (B / A)

In Fig.6 we found the current to peak resonances for loops with different perimeters (from 40 cm to 120 cm) and reports Width / Length (B/A = 1/4, 1/3...
and 2/5). We find in this figure a linear variation of these peaks as a function of the perimeter of these loops to the same ratio (B / A) thereof. Note that we have made loops whose resonant frequencies are between 400 MHz and 3 GHz.

The peak current amplitude at resonance can be easily connected to the perimeter of the loop by the following equation:

\[ I_{pic} = \alpha \cdot P \]  

(21)

With:

- \( I_{pic} \): The amplitude of peak current at resonance.
- \( \alpha \): The slope of the line.
- \( P \): Scope of the loop.

For the \( B / A = 1/4 \):

\[ \alpha_1 = 1.735 \times 10^{-3} = \frac{1}{4} \times 6.94 \times 10^{-3} \]  

(22)

For the \( B / A = 1/3 \):

\[ \alpha_1 = 2.353 \times 10^{-3} = \frac{1}{3} \times 6.94 \times 10^{-3} \]  

(23)

For the \( B / A = 2/5 \):

\[ \alpha_2 = 2.776 \times 10^{-3} = \frac{2}{5} \times 6.94 \times 10^{-3} \]  

(24)

From the above we can write \( \alpha \) as follows:

\[ \frac{\alpha_B}{\pi} = \frac{B}{A} \times K_t \]  

(25)

With:

\( K_t = 6.94 \times 10^{-3} \).

The equation can be written as follows:

\[ I_{pic} = \frac{B}{A} \times K_t \times P \]  

(26)

5.2 Evolution of the resonance frequencies of the induced currents in function of numbers of loops of rectangular spiral antennas (fixed perimeter).

The evaluation of the resonance peaks of currents on printed circuit tracks is crucial for designers of printed antennas. Indeed the action of these peaks can completely change the normal operation of the circuit.

We calculated the resonance frequency of the induced currents for four rectangular spiral antennas, respectively having a loop, two loops, three loops and four loops and the same perimeter 64cm, shown in Fig.7.

In fig.8 we observe that for the same scope the resonance frequencies of induced currents remain almost unchanged in function of the number of loops.
However, we notice a slight difference between the frequencies of resonance peaks of these antennas evaluated theoretically and those measured experimentally. This difference is surely due to the fact that in our theoretical model we do not take account of the dielectric permittivity of the substrate. Indeed, for the simulation we considered a spiral surrounded by air.

To account for the influence of the dielectric permittivity of the substrate on the positions of resonance frequencies, consider the case of a single loop. On Fig.9 we have plotted the $S_{11}$ parameter for different values of $\varepsilon_r$ substrate. We effectively note that this setting actually influence the position of the resonance frequency.

We can take advantage of this finding to try to design antennas that resonate at particular frequencies by playing on the nature of the dielectric substrates. This will allow the miniaturization of spiral antennas for RFID applications.

### 5.3 Evolution of the resonance frequencies of the induced currents in function of numbers of loops of rectangular spiral antennas (A and B fixed).

We have calculated the resonance frequencies of the induced currents for three rectangular spiral antennas, respectively having a loop, 2 loops and 3 loops and the same lengths $(A = 24\text{cm})$ and widths $(B = 8\text{cm})$: Fig.10

![Fig.10: Dimensions of tracks of printed antennas used in the simulation](image)

On Fig.11 we see that for the same lengths $(A = 24\text{cm})$ and width $(B = 8\text{cm})$ resonance frequencies of the induced currents can be easily represented by the following approximate relation:
With: $N=2, 3, 4, \ldots \ldots$

Fig.11: Frequencies of resonance in function of numbers of loops on the tracks of the ICs of the fig.10

6. Conclusion

This paper presents the design of antennas for passive RFID tags. The first part concerned the quick introduction of this technology. It was followed by modeling of a spiral RFID UHF antenna using the theory of the antennas.

Finally we have presented a method of estimating the peak current and resonance frequency of rectangular spiral RFID antennas.

This study showed that the amplitudes of the resonance peaks of rectangular spiral antennas printed vary linearly as a function of geometrical characteristics thereof. This linearity can be used by designers of printed antennas to assess the amplitude of current peaks at resonance with simple graphs that can be drawn as a function of geometrical characteristics of loops. Aswell as frequencies of resonance of the induced currents are virtually unchanged in function of numbers of loops for the same perimeter.

Currently we are trying to establish a relationship between the resonance frequency of such antennas and the nature of the dielectric substrate on which it is printed. This will surely improve the performance of printed antennas and also to contribute to their miniaturization.

References: