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Analysis, Design, and Manufacture of a Compact UHF RFID Tag Antenna for Operating in a Metallic or Non-Metallic Environments

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Abstract: A miniaturized tag antenna is presented in this paper, for operating in the RFID UHF American band, in free space or in a metallic environment. The proposed antenna is printed on a single layer FR4 substrate, and designed first to work in a free space. The shape of the π-match allowed us to achieve a good matching between the antenna impedance and that of the chip. The correspondence between simulation results in CST and HFSS pushed us to manufacture a prototype of our tag. After that, we simulated the proposed antenna in a metallic area, by adding a square metal plate separated with the antenna by a foam-layer, in order to test the performance of the tag in this environment. An optimization procedure enabled us to achieve a good performance when operating in metallic surroundings. Finally, we tested the reading range of the manufactured tag. We obtained a good range of about 6.5m. The final design of our proposed tag has a simple structure, a dimension of 51×26,63×0.8 mm^3 and which is reduced by 88,64% compared to the calculated theoretical dimensions of a patch antenna operating at the resonant frequency of 915 MH.

Keywords: UHF, RFID, Tag, Antenna, Miniaturized, Metallic environment, Free space, Read range.

1. Introduction

Radio-frequency identification (RFID) is considered as the most significant identification technology, because it is exploited in a wide range of fields such as positioning and identification of objects [1] or health monitoring with wearables [2], the Internet of Things [3] and communication with different sensors military, passport, supply chain, and so on [4]. This makes it inescapable in the daily life of the person.

The RFID system with allocated low frequency (125-134 kHz), high frequency (13.56 MHz), ultrahigh frequency (UHF) (860-960 MHz), and microwave frequency (2.45, 5.8, and 24 GHz) [5] has pulled attention for its variety of applications as of late. UHF-band RFID systems particularly provide long-range, faster reading and greater information storage capacity [6] than those operated in the low- and high- frequency (LF or HF) bands. For RFID UHF band, each country has its specific frequency band, i.e. 866-869 MHz for Europe, 902-928 MHz for North and South America and 952- 955 MHz for Japan [7]. Therefore, RFID tags are generally designed to work in a specific region.

The fundamental RFID system is made out of tag [8] from which we can remotely retrieve data, reader [9], and database where we stock identified object information. The physical connection between the reader and the tag is wireless and dependent on the electromagnetic coupling between their antennas. Exchange data between the tag and the reader is accomplished by near-field coupling with a load modulation in LF and HF bands, though, in UHF bands, the principle of backscatter modulation is utilized. In this method, the tag communicates with the interrogator by modulating the received signal and transmitting it back to the reader. The electric field of the propagating signal produces a potential difference crosswise the terminals of the tag antenna. This voltage is converted into DC voltage which powers up the chip. The latter acts as a switch to match or mismatch its internal load to the antenna by varying its input impedance leading to the effective modulation of the backscattered signal [10].

RFID tags can be divided into two classes: one is a passive tag, and the other is an active tag. Passive tags do not require an internal power source. They are energized by the reader's signal. In a passive RFID tag, the input impedance of the antenna is matched with the conjugate impedance of the tag IC for maximum power transfer from the antenna to chip [11]. Passive RFID microchips have capacitive impedances. In this manner, the antenna is designed with a larger inductive input impedance.

The accomplishment of tag antenna in design plays a crucial role in the RFID system particularly when it comes to passive operating mode. Because the size of the RFID tag depends only on the size of the antenna, size reduction of the tag antenna is an important concern in the design of compact RFID tags. The tag antenna must to be also designed with better communication qualities for longer detection range and high accuracy. Thus, impedance matching and miniaturization at the same time are the challenges in passive RFID tag antenna design.

Numerous techniques are proposed for the impedance matching such as T-match network [12], double T-matching structure [13] and inductively coupled loop [14]. Other techniques are used to reduce the antenna’s dimensions including meandering [15], which increase the electrical length of the tag antenna, fractal, inverted-F antenna (PIFA), Split Ring Resonators (SRR) structures, and slot's technique which consists of cutting slots of different shapes from a patch antenna [16-18].

In some applications, the tags require to be mounted on items of different kinds of materials, such as glass, wood, and even metallic objects like steel plates or steel containers. However, the interaction between the tag and the materiel makes the design of tag antenna challenging especially when the tag is mounted on conductive materials [19] or when it is placed in a metallic environment, due to totally different radiation boundaries. It can display a significant performance degradation due to a shift in operating frequency, distorted radiation patterns and impedance mismatch, which quickly reduce its read range or even cannot be read. To mitigate this problem, several antennas have been proposed in the literature. The most commonly used method is to incorporate a conductive ground plane beneath the antenna [20-22]. Printed inverted-F antenna (PIFA) is one of the commonly used structure for metal objects tagging. However, the fabrication cost for this antenna is high due to the existence of a shorting plate or shorting pin in the antenna design and they have also the drawback of a large size [23-25].

The motivation of this research is to design a novel RFID UHF size-reduced tag antenna working in a free space, with a simple configuration. The advantage of our design resides in the fact that it can also function in a metallic environment with a simple modification that consists in enlarging the substrate extremities. This shows that our antenna can operate in this area, with a simple configuration (planar) that does not contain a shorting plate or shorting pin in the antenna design, which reduces the manufacturing cost of our tag.

The antenna operates at the 902-928 MHz bands allocated for RFID applications in North and South America. The article is organized as follows: Section 2 describes the configuration of the proposed antenna. Section 3 is divided into two parts and presents the obtained results and a discussion for the proposed tag working in free space and in a metallic area. A table is also generated for comparing the proposed tag antenna with some other structures available in the literature, while a conclusion is made in Section 4 to summarize the paper.

2. Antenna design and Input impedance of the RFID chip

A miniaturized planar microstrip patch antenna for the UHF RFID tag is proposed and illustrated in Fig. 1. It has a very simple design and made out of a modified T-match linked at both ends with meander-line. To achieve conjugate matching between the tag chip (Alien Higgs-4) and the proposed antenna, the π- shape is applied. The folded dipole, which modifies the electrical length, is directly coupled to the π-structure resulting reduction of the physical size of the antenna and consists of a dipole, having a width of 0,75 mm, bent into a serpentine shape structure. The radiating element of the tag is printed on a thin, single-layer and inexpensive FR4 substrate (permittivity εr=4.4 and loss tangent tanδ=0.0025) with a thickness of h=0.8 mm and a total area of $46x2,63x0,8mm^3$. The antenna design is simulated using CST (Computer Simulation Technology) microwave studio [26], whose numerical analysis is based on the Finite Integration Technique, and the optimized parameters are enlisted in Table 1.

The input impedance of the microchip used in UHF RFID tags is capacitive. Tag antennas are designed to have an inductive impedance to deliver the maximum power transfer. The antenna's input impedance, Za should be the complex impedance conjugate of the chip, Zc (Zc= Za*). The Higgs-4 EPC global Class 1 Gen2 UHF RFID microchip fabricated by Alien Technology [27] is used. The chip packaging is SOT-323. It is easy to solder this sort of packaging manually. The foremost important advantage of using this chip is the minimum communication power of radio-frequency that can reach the level of -18.5 dBm. The input impedance of the microchip is Zc = 18,43−j181,2 Ω at 915 MHz. The impedance of the antenna is therefore intended for Za = 18,43+j181,2 Ω.

A parallel or series equivalent circuit Rp, Cp, Rs, Cs can model the RFID impedance. It is possible to calculate these parameters as shown in Eqs. (1) – (4) [28]. We have modeled this microchip in this work with a series equivalent circuit (Rs=18,43 Ω; Cs= 0.955 pF).

The equation parameters are as follows:

$$R_p = \frac{Im_{chip}^{\ 2} + R_{chip}^{\ 2}}{R_{chip}} \quad (1)$$

$$C_p = \frac{Im_{chip}}{2\pi f .(Im_{chip}^{\ 2} + R_{chip}^{\ 2})} \quad (2)$$

$$R_s = R_{chip} \quad (3)$$

$$C_s = \frac{1}{2\pi f .Im_{chip}} \quad (4)$$

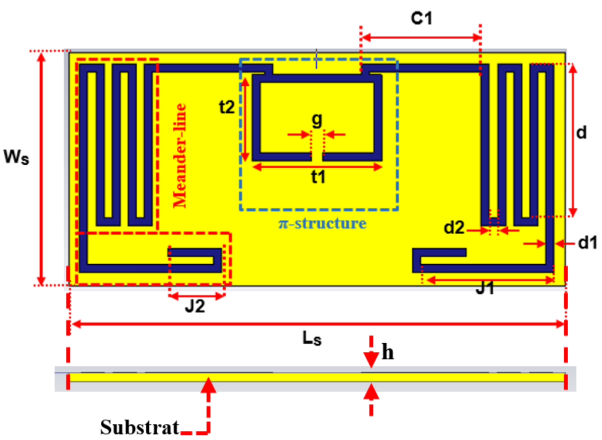


Figure. 1 Geometry of the proposed tag antenna

Table 2. Dimensions of the proposed tag antenna

Parameter	Value (mm)	Parameter	Value (mm)
Ls	46	d	15
Ws	21,63	d1	0,75
h	0,8	d2	0,75
t1	12	J1	13,15
t2	8	J2	5
C1	11,9	G	1

3. Results and discussions

First, a compact tag has been designed to operate in a non-metallic area. Then, simulations were carried out for the case when the tag was located in a metallic environment, in order to test the effect of a metal (copper plate) on the performance of our antenna. We placed a foam layer between the tag and the metal plate. After that, we have carried out a parametric study on the dimensions of the foam, the metal plate, and the substrate of our antenna, to see the impact of each one on the performances of our antenna.

3.1 Tag antenna for non-metallic surfaces

The simulated reflection coefficient characteristic of the designed antenna as a function of frequency is depicted in Fig. 2. It reaches a value of -24,13 dB at 915,6 MHz with a bandwidth of 12,29 MHz ranging from 909,69 to 921,98 MHz in CST, while, in HFSS, it is equal to -23,5 dB at 909 MHz extending from 903,4 to 915,1 MHz which means a bandwidth of 11,7 MHz. Because of the calculation method used in each software, we can observe a little distinction in return loss acquired with the two simulators. CST is based on the Finite Integration Technique (FIT) and HFSS is founded on the Finite Element (FEM) method [29]. Therefore, it remains an acceptable agreement between them. These values of S11 reflect that our antenna is well adapted.

Another parameter can demonstrate the antenna's adaptation: the input impedance. Fig. 3 illustrates the simulated real and imaginary part of the suggested tag antenna's input impedance. It is equivalent to Za= (21, 12 + 179, 8 j) and Za= (24,42 + 193,74 j) respectively at 915,6 MHz in CST and HFSS. These results are nearly equivalent to the value of the complex conjugate of the chip impedance Zc= (18,43-j181,2). This ends up in the observation that the π-shape has enabled us to accomplish a good conjugate matching between the antenna and the chip reducing the losses owing to reflections.

Fig. 4 shows the 2D simulated radiation pattern of the proposed tag antenna in E-plane and H-plane at 915 MHz. It is bidirectional in the E-plane and almost omnidirectional in the H-plane. We can notice that the gain reached a value of 0,83 dB and 1,2 dB respectively in CST and HFSS at 915 MHz.

Once the structure is validated using two simulators (HFSS and CST), the dimensions are fixed and the performance of the RFID tag is known, the tag is manufactured as shown in Fig.5. The RFID chip is soldered directly on the antenna through the two connection pads of the chip.

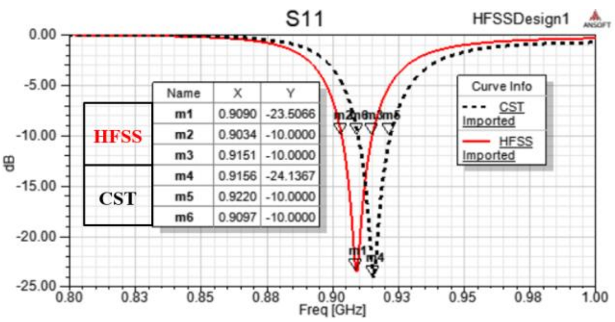
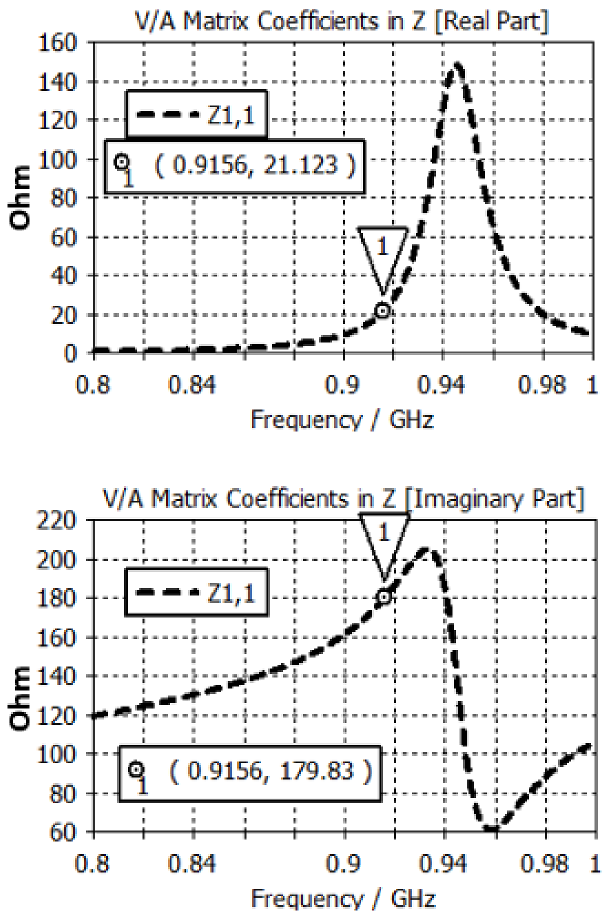
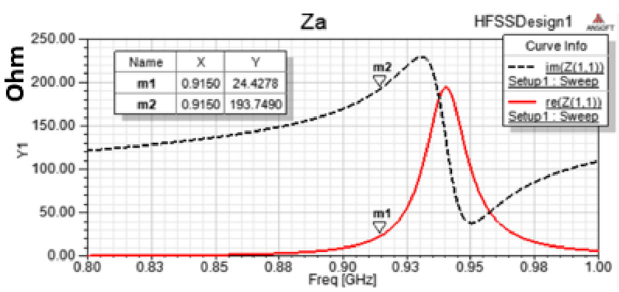


Figure. 2 Simulated return loss of the proposed tag antenna in CST and HFSS

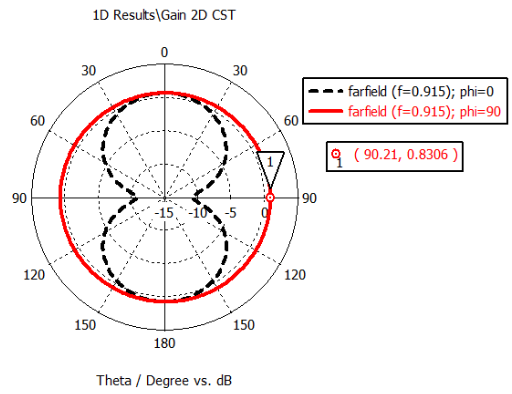


(a)

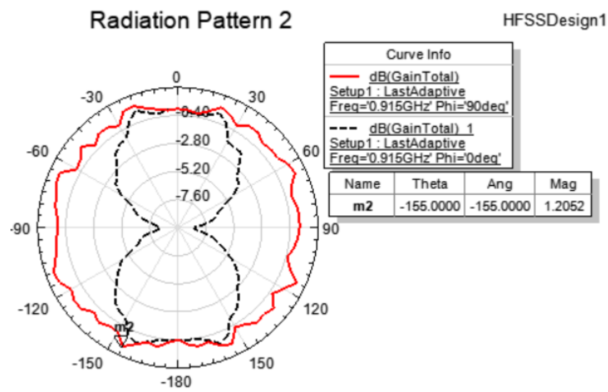


(b)

Figure. 3 Simulated input impedance of the proposed: (a) in CST and (b) HFSS

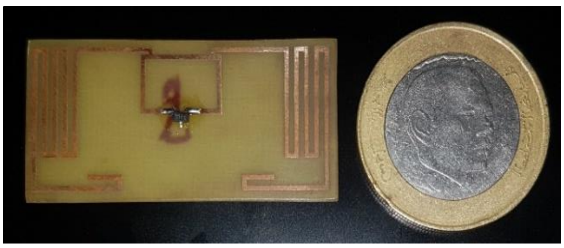


(a)

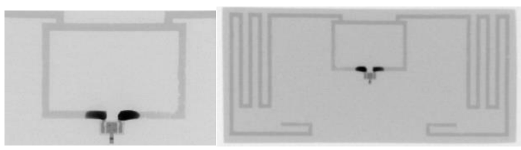


(b)

Figure. 4 Simulated radiation pattern of the proposed tag antenna in E-plane and H-plane at 915 MHz: (a) in CST and (b) HFSS.



(a)



(b)

Figure. 5 (a) Photograph of fabricated Tag antenna, and (b) Location of ALIEN H4 chip using X-Ray

3.2 Tag antenna for metallic environment

This time, we simulated our antenna with a metal plate to see its effect on our tag. A foam layer (polyethylene foam with εr = 1.03, and tan φ = 0.0001) [30] has been introduced between them, as shown in Fig. 6.

As we have already mentioned, when the RFID

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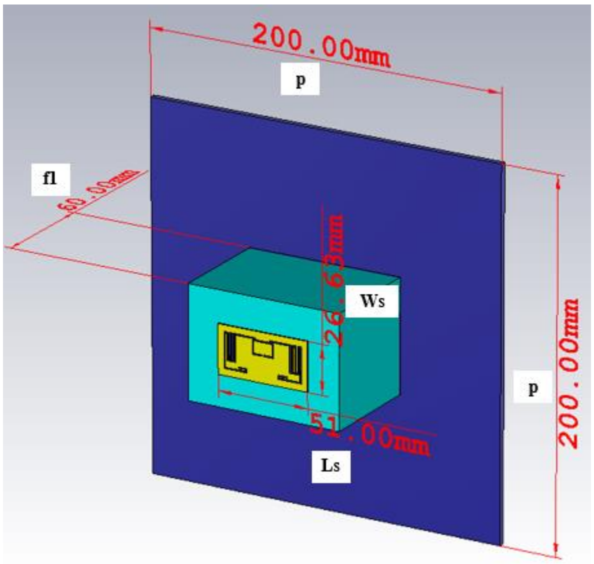

Figure. 6 Proposed tag for operating in a metallic environment

tag antenna is placed in a metallic enclosure or mounted on metal objects, this latter has a negative impact on the tag antenna's performance in terms of the resonant frequency and antenna impedance.

Therefore, to justify the choice of the prototype's final dimensions, a parametric study was conducted with CST on the effects of the metal plate to provide a better understanding of the antenna operation. The values in Table 1 are used for all simulations as reference dimensions. Simulations were performed on "f1", the thickness of the polyethylene foam, "p", the dimensions of the steel plate, and "f", the stretching of the substrate on the reflection coefficient of the proposed antenna.

The first step in our design is to choose the appropriate distance f1 to start with. The effects of variation the distance between the tag and the metal plate (f1) are depicted in Fig. 7. It can be clearly observed, from the figure, that the simulated impedance matching improves with increasing f1 from 40 to 80 mm. A value of 60 mm has been chosen as the appropriate value.

The impact of changing steel plate dimensions (p) is now examined and the results are shown in Fig. 8. The copper plate's size varies between 100 mm and 400 mm. It is seen from the graph that the resonance frequency shift to a higher frequency as p increases and the adaptation decreases. The best result was observed when the value of p was 200 mm.

Finally, we have optimized the substrate dimensions of the proposed antenna so that our tag can operate at the American band (902-928 MHz), the Chinese operating band (920-924.5 MHz) and the Korean and Japanese band (917-923.5 MHz), without

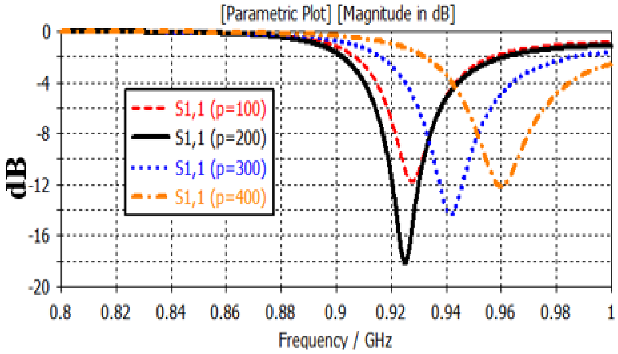

Figure. 7 The effect of the variation of "p" on the return loss

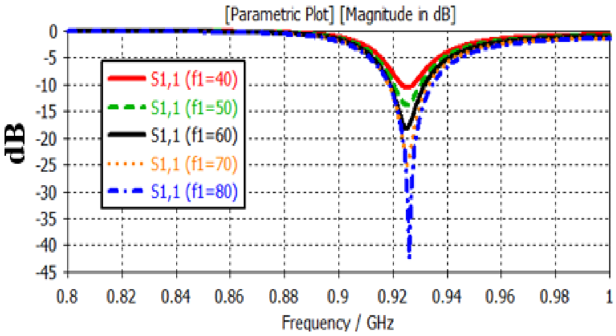

Figure. 8 The effect of various "f1" on the return loss

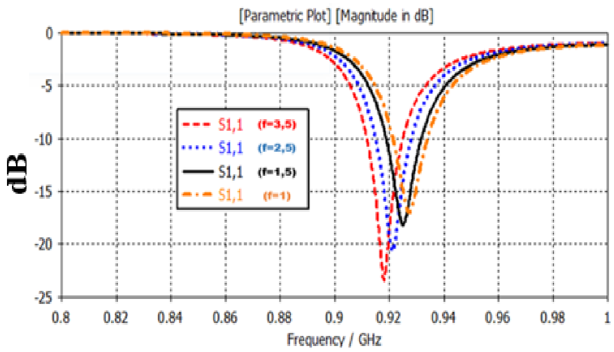

Figure. 9 The simulated reflection coefficient as a function of different values of "f"

modifying the original design. Fig. 9 plotted the reflection coefficient of our RFID tag with different values of "f" when "f1" and "p" are fixed at 60 mm and 200 mm respectively. It is observed that the resonance frequency shifts slightly towards lower frequencies and that the reflection coefficient increases with the rise of "f", which means that the adaptation improves with the enlargement of the substrate. The best result was observed when the f-value was 2.5mm.

3.3 Simulations results of the proposed tag without metal and close to a metal plate

Fig. 10 shows the simulated reflection coefficient of the proposed tag antenna with and without metal.

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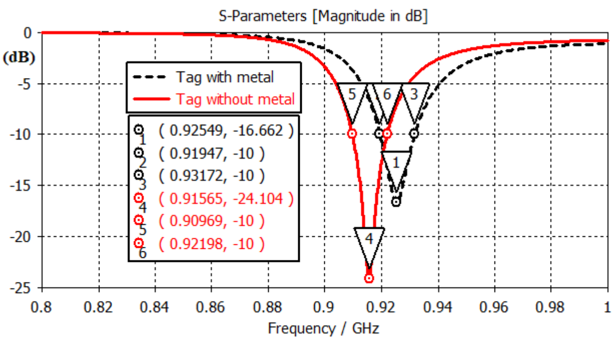
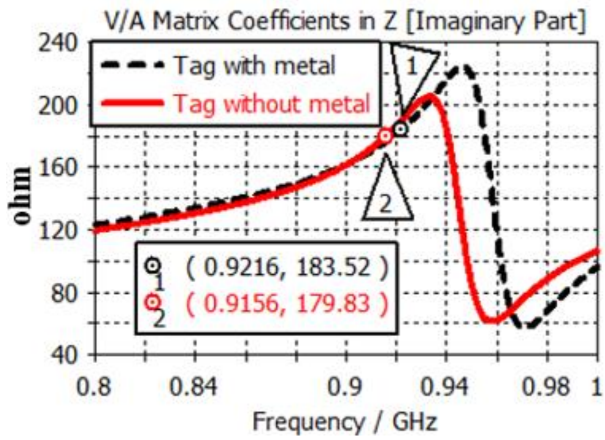
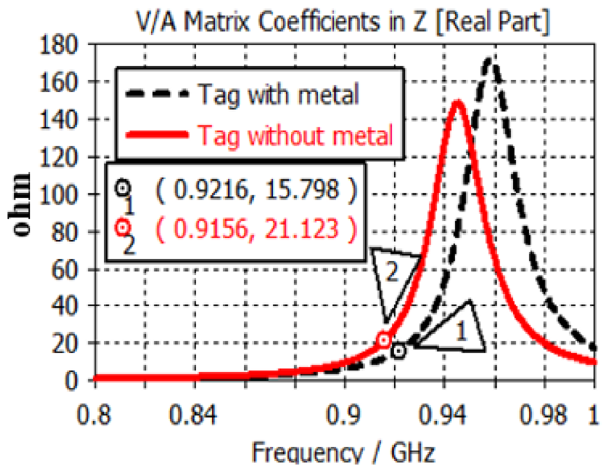


Figure. 10 Simulated reflection coefficient of the proposed tag with and without metal



(a)



(b)

Figure. 11 Simulated Input impedance of the proposed tag with and without metal: (a) real part and (b) imaginary part

We notice that the simulated return loss, of our tag without a metal plate, reaches a value of -24,13 dB at 915,6 MHz with a bandwidth of 12,59 MHz ranging from 909,69 to 921,98 MHz. While, for the tag with metal (in a metallic area), we obtained a bandwidth of 12,25 MHz (915,5-928,09 MHz) with a value of S11 of -18,7 dB at the resonant frequency of 921,6

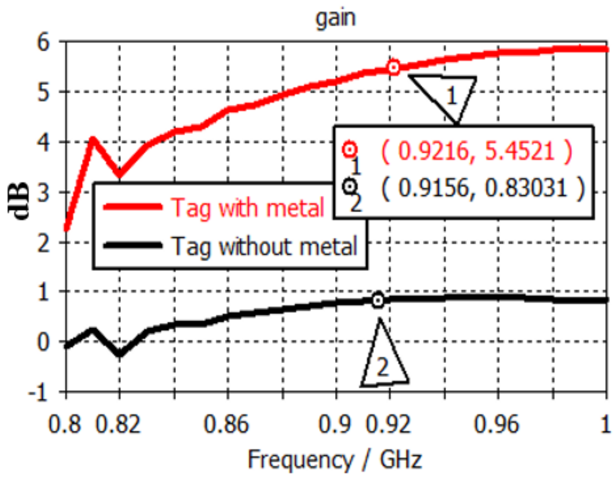


Figure. 12 Simulated gain, as a function of frequency, of the proposed tag with and without metal

MHz. The simulated resonance frequency of the metal tag antenna has been shifted by about 6 MHz to higher frequencies compared to the metal-free tag (in the open air).

The following figure (Fig.11) shows the simulated real and imaginary part of tag impedance as a function of the frequency. It is equal to Za=179,83 + j 21,12 Ω and Za=183,52 + j 15,79 Ω for the tag in free space and for the tag mounted on a metal plate respectively and therefore having excellent impedance match with the chip impedance which is Zc=18,43+j181,2 Ω. Good impedance matching could ensure a longer antenna reading distance, which is an important condition for RFID applications.

Fig. 12 shows the simulated gains of our tag with and without metal. When the proposed tag was placed in free space, a peak gain of about 0,83 dB at 915,6 MHz was obtained. However, the peak gain reaches 5,45 dB at 921,6 MHz when the tag was placed closer to the metal. This is due to the fact that the metal plate is a conductive element.

A satisfactory simulation results were obtained for the tag when it is placed near the metal. Therefore, our antenna can operate in a metallic environment. The difference between the tag structure in free space and in metallic surroundings is the spreading of the substrate (2.5 mm on each side) for the tag when it is located in the proximity of the metal.

3.3 Theoretical and measured read range

Among the vital properties for the design of the RFID tag is the reading range. It brings us information about the maximum distance at which the tag receives the minimum threshold power needed to turn on and scatter a signal back, and therefore the maximum distance at which the reader

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can detect the tag antenna. The theoretical reading range can be obtained using Friis-free space equation formula (Eq. (5)) [31]:

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP.G_t.\tau}{P_{chip}}} \quad (5)$$

λ is the wavelength and EIRP is the effective isotropically radiated power (4 W in the USA) determined by local country regulations. Pchip is the minimum threshold power necessary to activate the chip, Gt is the gain of the receiving tag antenna, and τ is the power transmission coefficient. Hence, the calculated maximum read range was found to be 14.48m at 915 MHz.

The reading range of the tag antenna was measured in the situation in Fig.13 at MASCIR Center. The measuring system is made up of a host, a reader controller (F5860-H), a circularly polarized reader antenna (A4108), and the fabricated tag as shown in the Fig.13. The reference reader antenna has a frequency range of 840 to 960 MHz and a gain of 8dBi. The input power of the reader antenna is 1W (30dBm). The whole system is controlled by software developed at MASCIR Center.

We can see, from Fig.13, that the maximum measured reading range is 6.5m. We notice that it is lower than the theoretical value (14.48m) calculated using the Friis equation. This difference is due to the presence of the metal in the tag's environment as proved in the figure.

In order to valorize our proposed tag, we compared our design with various tags recently published in the literature, operating in a metallic milieu. This comparison, illustrated in Table 2, is made in terms of the overall dimensions of the antenna, the reading range, the use or not of the short-circuit elements and finally the dimensions of the metal plate. Referring to Table 2, we can clearly see that the volume of the proposed tag is less voluminous than the other antennas, which means that it has the compact size. In addition to its compactness, it has a simple structure that does not contain any short-circuit elements (vias and pins), which makes it easy to manufacture with a reduced cost. In terms of reading distance, our tag has a longer reading range than the tags published in [23, 24], and almost similar to that of [25]. We can conclude that our tag offers an optimal reading range compared to its miniature size. In addition to its good radiation and adaptation performance, as well as its simple structure, our antenna can be a good candidate for tags operating in metal or non-metal environments in the UHF band.

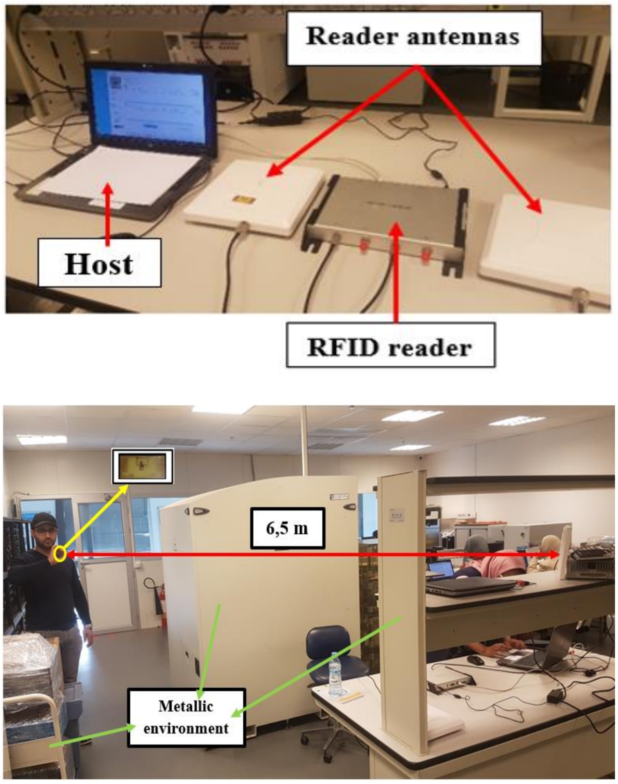

Figure. 13 Measured read range of the proposed RFID tag antenna

Table 2. Comparison of the proposed tag in a metallic environment with other designs

	[23]	[24]	[25]	**This work**
Size (mm^3)	60×60×1,6	35×100×3	45×45×1,27	**51×26,63×0,8**
Read range	4,8	5,5	6,8	**6,5**
Shorting elements	Pins	Vias	Vias	**No**
Metal plate size (cm)	15×15	21×13	30×30	**20×20**

4. Conclusion

A novel compact tag antenna for passive UHF RFID applications is presented. It is set on the economical FR4 substrate and has a dimension of 46 x 21,63 x 0,8 mm^3.in the case of operating in a free space. It can even work in metallic environment with the enlargement of the substrate of 2.5mm from each side which means a total size of 51 x 26,63 x 0.8 mm^3. It provides a stable performance when it is placed in a metallic milieu and reached a measured read range of 6.5m. This miniaturized tag is reduced of about 88,64 % compared to the calculated theoretical dimensions of a patch antenna operating at the resonant frequency of 915 MH. Due to its small profile, low-cost substrate, and the fact that it does not contain a ground plane, short-circuit pins or probes, the antenna can be easily manufactured, potentially reducing costs. A prototype of the tag antenna was fabricated. Such a tag design is found to be very promising for metallic or non-metallic UHF RFID applications.

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