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Patch Antennas with T-Match, Inductively Coupled Loop and Nested-slots Layouts for Passive UHF-RFID Tags

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The objective of this article is to study the performance of the RFID (Radio Frequency Identification) technology and especially the passive UHF RFID (Ultra High Frequency RFID) tags by mean of simulation. In this paper, three patch antennas with different matching techniques for passive UHF-RFID tags are proposed. T-Match, inductively coupled loop and nested-slots layouts are adopted in order to achieve complex impedance matching between the antennas impedance and the chip selected at 915 MHz with high performance. The antennas are printed on a Rogers RT/duroid 5880 substrate with a relative permittivity of 2.2 and thickness of 1.575 mm. Studies demonstrate that the inductively coupled loop and the nested-slots matching techniques are the good candidates to adapt the antenna impedance to chip impedance, while adaptation in T is intended to be only used for dipole antennas. We have achieved an adaptation of 99.90 %, a very wide bandwidth of 409.6 MHz, a broadside an asymmetrical radiation pattern in the *E*-plane, a read range of 21.19 m and an antenna gain of 4.17 dB with the inductively coupled loop matching technique, while with the nested-slots matching method, we have acquired an adaptation of 99.94 %, a directive antenna, a read range of 19.83 m and a gain of 3.59 dB.

Keywords: RFID, Antenna, UHF-RFID, T-Match, Inductively couped loop, Nested slots.

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1. INTRODUCTION

RFID means Radio Frequency IDentification, it is the generic term of technology that uses the radio waves to detect, locate and identify objects bearing smart labels when located in a reader field. RFID have many applications and massively deployed in medical field for patient identification and monitoring, for prevention of medical errors and for tracking documents and samples [1]; in logistics, precisely for supply chain management [2] and it is also used for objects and animals' traceability [3], etc.

An RFID system constituted of two functional blocks: a reader and a tag [4, 5]. The reader is the interrogator of RFID system who sends synchronization, energy required to activate the tag. The tag is the target of RFID system which contains a unique code allows to reader to identify objects on which the tags are attached. The RFID tag also consists of two main elements: an RFID chip and an antenna [5]. In order to use antenna efficiently it must be adapted [6, 7]. Indeed, the input impedance of RFID chip is very reactive and less resistive compared to the antenna input impedance. In order to obtain a good adaptation allowing maximum power transfer between the antenna and chip, it is necessary that the antenna input impedance equal to the conjugate impedance of the chip. Several techniques have been discussed in literature to achieve complex impedance matching at the desired frequency with high performance, such as: adaptation by serial elements [8, 9], by parallel elements [9] and by magnetic coupling [9], but the most used are the T-Match structure [10, 11], the inductively coupled loop [12, 13], and the nested-slots [14]. The first three methods cited are used to adapt the dipole type antennas impedance, while the last three techniques are used to match the patch antennas impedance, precisely the nested slots.

In this work, the focus will be on designing a passive UHF-RFID patch antennas and matching their impedances to a specific chip using T-Match, inductively coupled loop and nested-slots techniques, then compared the performances of the antennas proposed in terms of the impedance matching, reading distance, gain obtained, radiation behavior, as well as antennas size.

The rest of this paper is organized into four main sections. Section 2 introduces different techniques that we have adopted for achieving complex impedance matching between the antenna and chip such as: T-Match, inductively coupled loop and nested-slots layouts. The patch antennas performances at different configurations are compared in section 3. Finally, some conclusion and perspectives are presented in section 4.

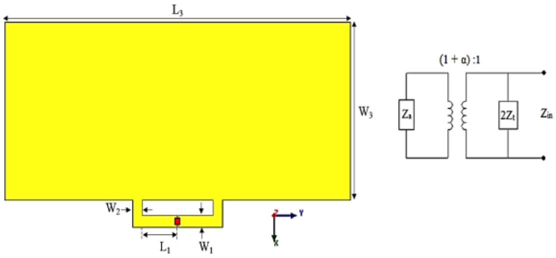
2. ANTENNA DESIGN AND ANALYSIS

2.1 T-Match Adaptation Technique

This type is the most used for passive UHF-RFID tags because it allows adaptation between the antenna impedance and chip impedance at the desired frequency by means a simple and reliable structure, without causing a significant increase at the cost. This technique is based on insertion a folded dipole, connected to radiating element center, then modeled the antenna constitutes of the radiating body and insertion by an equivalent circuit, to be able to calculate the dimensions of the folded dipole in order to achieve an antenna impedance equal to the conjugate of chip impedance. To calculate the antenna input impedance in T-Match configuration, the radiating body and insertion (Fig. 1a) are modeled by the circuit illustrated in Fig. 1b.

The results were presented at the International Conference on Innovative Research in Renewable Energy Technologies (IRRET-2021)

It has been proved in [7, 10, 11] that the impedance at the source point of the antenna is given by equation (1):



a b

Fig. 1 – Patch antenna in T-Match configuration: (a) antenna geometry, (b) equivalent circuit

$$Z_{in} = \frac{2Z_t[(1+\alpha)^2 Z_a]}{2Z_t + (1+\alpha)^2 Z_a}, \quad (1)$$

where:

Z_a: the impedance of the radiating element when the T-Match link is absent,

Z_t: the input impedance of shorted stub formed by the transmission line of two length conductors $a/2$, of thickness w and separation b, $Z_t = jZ_0 \tan\left(k\frac{a}{2}\right)$,

K: the wave number,

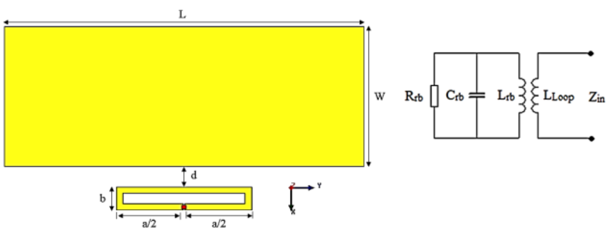
Z_0: the characteristic impedance of the transmission line formed by the two conductors (the T-Match link and the radiating element), $Z_0 \approx 276\log_{10}\left(\frac{L_2}{\sqrt{r_e r'_e}}\right)$,

α: the current division factor between the two conductors (the T-Match link and the radiating element),

$$\alpha = \frac{\ln\left(\frac{L_2}{r'_e}\right)}{\ln\left(\frac{L_2}{r_e}\right)}.$$

2.2 Inductively Coupled Loop Matching Technique

The impedance matching of passive UHF-RFID tags antennas can also be done using a small inductive coupling loop placed proximity the radiant body. In this case, the antenna is constituted of a small rectangular loop whose two terminals are connected directly to the chip, and a radiant body; the two elements are inductively coupled, and the coupling force is controlled by distance between the loop and the radiating element.



a b

Fig. 2 – Patch antenna with the inductively coupled loop feeding structure: (a) antenna geometry, (b) equivalent circuit

Fig. 2a presents the patch antenna with the inductively coupled loop feeding structure and Fig. 2b illustrates the equivalent circuit.

As shown in Fig. 2b, the loop was modeled by a transformer and the impedance at the source point of the antenna was calculated by equation (2) [11, 13, 14]:

$$Z_{in} = Z_{Loop} + \frac{(2\pi f M)^2}{Z_{rb}}, \quad (2)$$

where:

Z_{Loop}: the impedance of the inductive coupling loop, $Z_{Loop} = j2\pi L_{Loop}$,

L_{Loop}: the self-inductance of the feeding loop,

M: the mutual inductance between the radiating body and the feeding loop,

Z_{rb}: the impedance of the radiating element around the resonance frequency f_0. This impedance can be expressed using the radiation resistance R_{rb}, the quality factor Q_{rb} and the resonant frequency f_0 by equation (3):

$$Z_{rb} = R_{rb,0} + jR_{rb,0}Q_{rb}\left(\frac{f}{f_0} - \frac{f_0}{f}\right). \quad (3)$$

At the resonance frequency $f = f_0$ the resistive and reactive part are given by equations (4) and (5), respectively:

$$R_{in,0} = R_{in}(f = f_0) = \frac{(2\pi f_0 M)^2}{R_{rb,0}}, \quad (4)$$

$$X_{in,0} = X_{in}(f = f_0) = 2\pi f_0 L_{Loop}. \quad (5)$$

From (4) and (5), the resistive part of the antenna input impedance ($R_{in,0}$) at the resonance frequency (f_0) depends only to the mutual inductance M, i.e. to the distance between the antenna and the loop "d", while the reactive part $X_{in,0}$ depends only on the self-inductance L_{Loop}, i.e. to the dimensions of the loop "a" and "b", which shows that the resistive and reactive part can be set independently by acting respectively on the distance between the radiating element "d" and the loop dimensions (a, b).

2.3 Nested-Slot Matching Technique

Nested-slot technique is a completely different adaptation method that assures matching between the antenna impedance and chip impedance using one or more slots printed on the radiating body [11]. This method is generally used to design the tags antennas proximity to metal because it allows high impedance matching on high permittivity substrate [16]. At most the reactive inductive effect which introduces this technique, also minimizes the antennas size and bring up several resonance frequencies [11-16]. Fig. 3 shows the patch antenna with the nested slots.

3. ANTENNAS DESIGN APPROACH

In this paper, maximizing the power transfer between the antennas and chip is the major challenge. To achieve this aim, T-Match, inductively coupled loop and nested-slots techniques are adopted and a comparison between them are achieved.

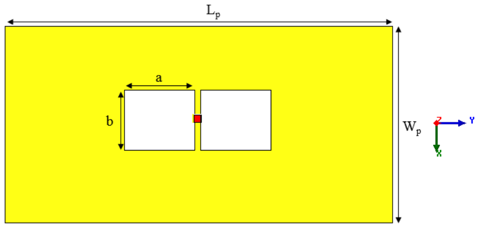


Fig. 3 – Patch antenna with the nested slots

In Fig. 4a, the patch antenna impedance is adapted to chip impedance by insertion a folded dipole, connected to radiating element center or adaptation in T.

To compare the performances of T-Match configuration, to the others matching techniques, first, and as shown in Fig. 4b, the antenna is coupled to the chip through a small inductive loop placed proximity the radiant body (Inductively coupled loop method), and then the matching is assured by printing the slots on the radiating body or nested-slots configuration (Fig. 4c).

Fig. 4 shows the proposed patch antennas geometries, and the detailed dimensions are listed in Table 1.

The antennas are printed on a single layer Rogers RT/duroid 5880 (tm) substrate with dielectric constant of 2.2, loss tangent of 0.0009 and thickness of 1.575 mm.

For the three configurations, the chip used is "NXP UCODE G2iL". It has a sensitivity threshold of – 18 dBm and an input impedance of (23 – *j*224) Ω at 915 MHz.

As shown in Table 1, for both matching techniques: T-Match and inductively coupled loop, we have obtained an antenna size of 67 × 110 × 1.575 mm^3 while for nested-slots method, we have acquired an antenna size of 100 × 100 × 1.575 mm^3.

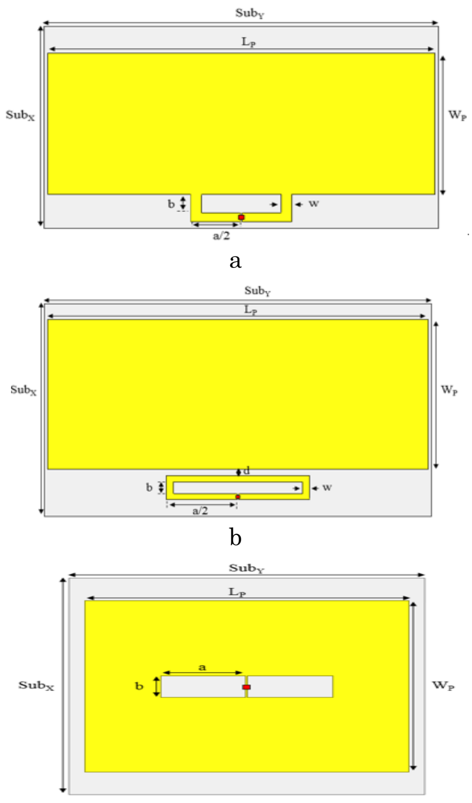


Fig. 4 – Patch antennas geometries using: (a) T-Match configuration, (b) inductively coupled loop feeding structure, (c) nested-slots

Table 1 – Patch antennas dimensions in [mm]

	Sub$_X$	Sub$_Y$	L_P	W_P	a	b	d	w
T-Match	67	110	47	108	27.6	6.1	0	3
Loop	67	110	47	108	40.1	3.6	2	2
Nested slots	100	100	91	78.9	24	9.9	0	0

4. SIMULATION RESULTS AND DISCUSSION

The proposed patch antennas were modeled, optimized and simulated using HFSSTM (version 15).

Fig. 5 shows the simulated return losses at 915 MHz. We have obtained a reflection coefficient of – 46.86 dB and a bandwidth of 32.6 MHz for the patch antenna in T-Match configuration. With the inductively coupled loop feeding structure, we have acquired a reflection coefficient of – 49.94 dB and more than that attained in T-Match adaptation technique but with a fairly wide bandwidth of 409.6 MHz. For the patch antenna with nested-slots matching technique, we have attained a reflection coefficient of – 62.83 dB and a selective bandwidth that covers the entire of American band [902-928] MHz.

Fig. 6a and Fig. 6b show respectively the resistive and reactive part variation according to the frequency variation. As indicated in the figures, at the resonance frequency (915 MHz) and for the three adaptation techniques, we have achieved a high impedance matching between the proposed antennas and chip selected. We have acquired an antenna impedance of (24.81 + *j*223.07) Ω with adaptation in *T*, an antenna impedance of (21.74 + *j*223.31) Ω with the inductively coupled loop structure while for nested slots matching technique, we have obtained an antenna impedance of (22.76 + *j*224.10) Ω.

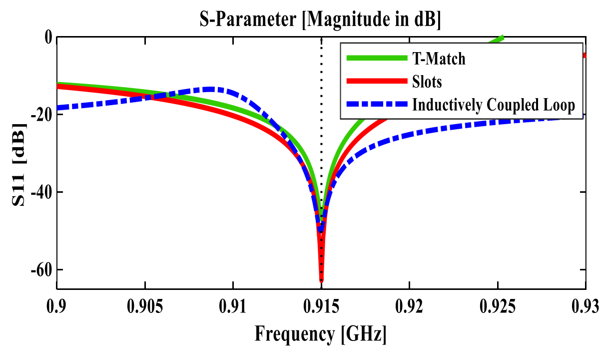
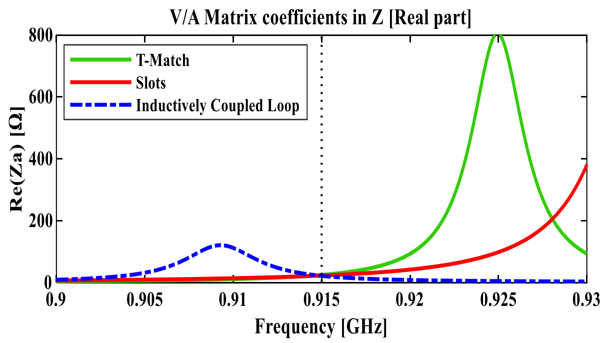


Fig. 5 – The return loss (S_{11}) in [dB]



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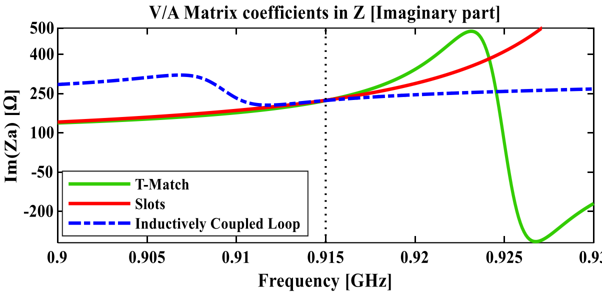


b

Fig. 6 – Patch antennas input impedance in [Ω]: (a) resistive part, (b) reactive part

In radio frequency identification systems, the tags antennas performances are measured in terms of distance from which the reader can detect the backscatter signal sent by the tag or the reading distance.

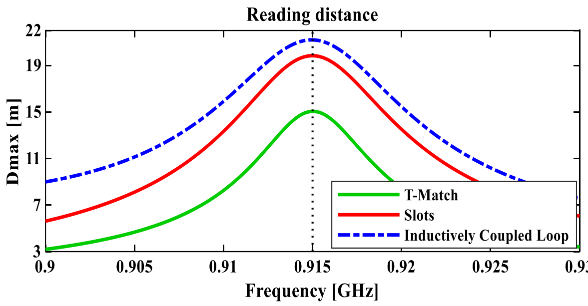
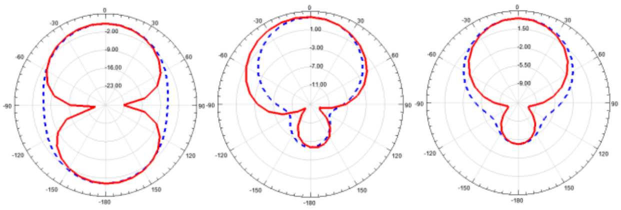


Fig. 7 – Reading distance in [m]

Fig. 7 presents the maximum reading distance achieved for the proposed patch antennas using T-Match, inductively coupled loop and nested-slots configurations. According to this figure, the maximum reading distance obtained in free space is of 15.05 m in T-Match configuration, while it is of 21.19 m for the patch antenna with inductively coupled loop structure and around 19.83 m for the nested-slot configuration, which shows that the reading range depends directly to the antenna gain.

Fig. 8 shows the simulated 2D radiation patterns in *E* and *H* planes (*xz* and *yz* planes). The patch antenna with adaptation in *T* presents an almost omnidirectional (doughnut shaped) radiation pattern in *E* plane, while in *H* plane presents an omnidirectional radiation pattern like the behavior of a dipole antenna and with a gain of 1.20 dB, which shows that this type of adaptation is intended to be used for dipole antennas than for patch antennas. In the *E*-plane and at 915 MHz, for the patch antenna with the inductively coupled loop feeding structure, the radiation patterns are broadside and asymmetrical and the half-power beamwidth is of 108°, while in the *H*-plane, the radiation patterns are broadside and symmetrical and the half-power beamwidth is of 84°. In this configuration, the antenna gain achieved is of 4.17 dB. For patch antenna with nested-slots structure, the radiation patterns are broadside and symmetrical unlike to the inductively coupled loop configuration and the half-power beamwidths are 89° and 102° in *E* and *H* planes, respectively, and we have obtained an antenna gain of 3.59 dB at 915 MHz.



a b c

Fig. 8 – Radiation patterns at 915 MHz; *E*-plane (solid line) and *H*-plane (dashed line): (a) T-Match, (b) inductively coupled loop, (c) nested-slots

Table 2 presents a comparison between the antennas performances in terms of resonance frequency, reflection coefficient, bandwidth, load impedance, gain, and reading distance.

Table 2 – Patch antennas performances

	f_r [MHz]	S_{11} [dB]	BW [MHz]	Z_A [Ω]	G [dB]	D_{max} [m]
T-Match	915	– 46.86	32.6	24.81 + *j*223.07	1.2	15.05
Loop	915	– 49.94	409.6	21.74 + *j*223.31	4.17	21.19
Nested Slots	915	– 62.83	35	22.76 + *j*224.10	3.59	19.83

5. CONCLUSIONS

In this paper, three patch antennas with different configurations for passive UHF-RFID tags are proposed. In order to achieve complex impedance matching between the antennas impedance and the chip selected at the desired frequency, the T-Match, the inductively coupled loop and the nested-slots techniques are adopted and a comparison between them are achieved. We have obtained a patch antenna behaves like dipole in its radiation pattern with a gain of 1.20 dB at 915 MHz using the T-Match configuration. With the inductively coupled loop matching technique, we have acquired an adaptation of 99.90 %, a very wide bandwidth of 409.6 MHz, a broadside an asymmetrical radiation pattern in the *E*-plane and an antenna gain of 4.17 dB for and with the nested-slots layout technique, we have achieved an adaptation of 99.94 %, an antenna with a selective bandwidth that covers the entire American band [902-928] MHz, a roughly directive antenna in the *E*-plane and a gain of 3.59 dB.

In a future work, research will be oriented to design a patch antenna for the passive UHF-RFID tags applications in metallic supports.

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Патч-антени з Т-подібною схемою, індуктивно зв'язаним контуром та макетами вкладених слотів для пасивних тегів UHF-RFID

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Метою статті є вивчення можливостей технології RFID (Radio Frequency Identification), а особливо пасивних тегів UHF-RFID (Ultra-high frequency RFID) за допомогою моделювання. У роботі пропонуються три патч-антени з різними методами узгодження пасивних тегів UHF-RFID. Т-подібна схема, індуктивно зв'язаний контур та макети вкладених слотів використовуються для складного узгодження імпедансів між опорами антен та мікросхеми, обраною на частоті 915 МГц з високою продуктивністю. Антени друкуються на підкладці Rogers RT/duroid 5880 з відносною діелектричною проникністю 2,2 та товщиною 1,575 мм. Дослідження демонструють, що індуктивно зв'язаний контур і методи узгодження вкладених слотів є гарними кандидатами для адаптації імпедансу антени до імпедансу мікросхеми, тоді як адаптація в Т-подібній схемі передбачає використання лише для дипольних антен. Ми досягли адаптації 99,90 %, дуже широкої смуги пропускання 409,6 МГц, широкої асиметричної діаграми спрямованості в площині *E*, дальності зчитування 21,19 м і коефіцієнта підсилення антени 4,17 дБ за допомогою техніки узгодження індуктивно зв'язаного контуру, в той час як за допомогою методу узгодження вкладених слотів ми отримали адаптацію 99,94 %, напрямлену антену, дальність зчитування 19,83 м і коефіцієнт підсилення 3,59 дБ.

Ключові слова: RFID, Антена, UHF-RFID, Т-подібна схема, Індуктивно зв'язаний контур, Вкладені слоти.