Matching Approach for UHF RFID Tag Antenna Immersed in Dielectric Materials

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Abstract

In this paper, a novel UHF RFID Tag antenna for automotive tire is presented. The antenna shape and size are reduced by using a meander line. To ensure a proper impedance matching between the antenna and the microchip, especially when antenna is immersed in dielectric medium, a simple approach is presented. The square-load is added at the both ends of antenna tag in order to improve the bandwidth aspect. The tag has a reduced size: $40mm * 13.5mm * 0.018mm$. Hence, it can be embedded in automotive tire. The tag provides the low profile and low cost fabrication. The simulated results show that our approach is helpful to achieve impedance matching process. Moreover, the proposed antenna has omnidirectional radiation patterns and a good gain that satisfy maximum power transmitting in RFID communication once tag is embedded in rubber material.

Keywords: Antenna, Radio Frequency Identification (RFID), Tag, Automotive tire, Dielectric medium

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1. Introduction

In recent years, radio frequency identification (RFID) has become very popular in many applications domains, such as purchasing and distribution logistics,

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manufacturing companies and material flow systems. That provides wirelessly information about different items [1]. The adoption of this technology is not only limited to these application domains but it is greatly used with sensors to collect physical information about different items [2]. The large-scale implementation of the RFID technology revolutionized also the Internet of Things (IoT) [3, 4, 5].

In RFID technology, the transponders "tags" can be classified in two main categories: active (with power supply) or passive (no power supply) [6]. The active tags need power survey in order to ensure it function while passive tags exploit only the radio frequency energy radiated by transceiver. These latter communicate with the base station (reader) using a specific operating frequency. Each country adopts one special frequency band for RFID technology [7]. The repartition of the Ultra High Frequency (UHF) band is as follows: 866–869 MHz in Europe, 902–928 MHz in North and South America, and 950–956 MHz in Japan and some others Asian countries. A typical passive RFID tag is composed of two key elements: an antenna and an application specific integrated circuit (ASIC) chip [8].

A passive RFID system operates in the following way (see Fig. 1). A reader antenna transmits a query signal which is captured by the tag antenna. The radio frequency (RF) voltage established on tag antenna is converted to direct current [9]. This voltage activates the chip, and then the tag sends data back by varying its input impedance. The impedance usually switches between two different states: conjugate match and some other impedance values. That successfully modulates the back-scattered signal [9]. The RFID system does not need line-of-sight to collect information about interrogated items [10, 11]. Therefore, an RFID tag can be embedded into objects.

Most of RFID antenna do not work correctly when embedded in highly dielectric medias. Because the antenna was designed to match a specific ASIC chip impedance and tested in ideal conditions. However, the medium where antenna is embedded changes drastically the input impedance of the antenna. Generally, to develop a robust RFID system for automotive tire, there are two

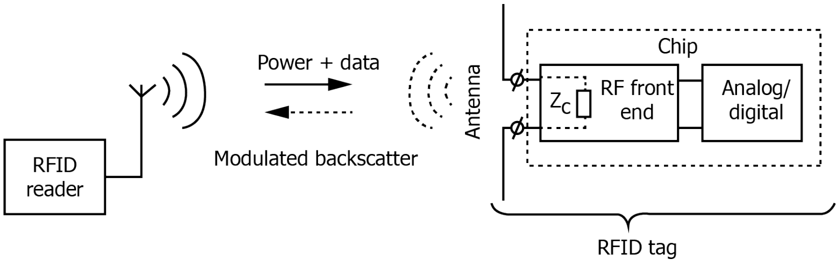


Figure 1: RFID system operation adopted from [18]

essentials challenges [11]. The first one is reliability and efficiency of the RF link between the tag and reader. The second one relates to tag's structural persistence and durability. Further, the tag antenna must have the following performances: *(i)* compact size to be attached to the required objects; *(ii)* omnidirectional radiation patterns; *(iii)* good impedance matching; *(iv)* be robust to endure the mechanical effects caused by the tire while moving; *(v)* be cheap.

In passive RFID tag, the antenna should be self-resonant [12]. Therefore the matching circuit is integrated on antenna design to ensure low cost, low profile and maximum transmitted power between tags and reader. It is worth noting that ASIC chip has a complex impedance in terms of real and imaginary part. However ensuring proper impedance match is a challenging step.

In this work, we present a UHF RFID tag antenna designed for automotive tire. The size reduction technique is performed by using a meander line, whereas impedance matching is investigated in free space and in rubber media based on our approach. Besides, antenna shape and used materials are appropriate for low cost fabrication. The rest of this paper is structured as follows. Section 2 discusses our design methodology that led us to design the antenna, while section 3 presents the results and discusses the performances of the proposed antenna. Finally, section 4 offers a brief conclusion.

2. Tag Antenna Design

2.1. Size Reduction

One of the most used methods to reduce antennas size is meandering (see Fig. 2). This technique has been widely implemented in RFID system to minimize the overall tag size. It is an attractive choice for size reduction purpose. Folding the elements in a meander produces resonances at much lower frequencies than the case of straight antenna element of identical length [12]. Because in a meandered line, adjacent vertical segment produces a wire configuration with both capacitive and inductive reactance, which cancel each other out (they have opposite phase) [13, 14]. These transmission lines contribute to the storage of electric energy and losses and do not give an appreciated impact for radiated power [15]. Numerically experienced, it is worth noting that we can shift down the resonance frequency if we increase the length of the vertical segments. In general, having a reduced antenna size is not enough. To build a robust RFID system, the designer must investigate the impedance matching purpose.

2.2. Impedance Matching

For RFID tags, the surrounding environment may influence the antenna characteristics and may detune the resonance frequency. For our case, the tag should be embedded in automotive tire. This latter presents different highly dielectric and loss material with variable thickness [16]. These environmental properties must be expected while designing tag antenna. Therefore, a proper impedance matching process, taken into account the ASIC chip and the surrounding environment, has a valuable contribution to enhance the RFID system performances. The ASIC chip is directly connected to antenna. Hence, the impedance matching network should be designed with it.

A typical passive tag consists of an antenna and an ASIC chip. Both exhibit the respective complex impedance $Z_a(f, \Phi) = R_a + jX_a$ and $Z_c(f) = R_c + jX_c$, where $Z_a(f, \Phi)$ is the input impedance of the antenna and $Z_c(f)$ is the input impedance of the chip [17]. Φ refers to several parameters such as variation

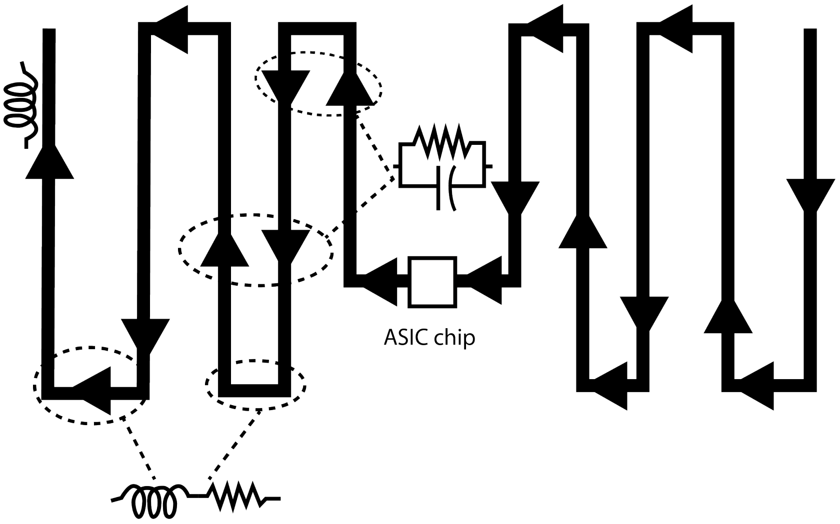


Figure 2: The geometry of a meander-line antenna having multiple turns. The horizontal lines control the radiation resistance, the adjacent vertical lines give storage of electric energy and loss

in surrounding environment, propagation conditions and noise. The antenna impedance depends not only on its structure but also on the surrounding environment. More precisely, its equivalent circuit model can be simply described using Thevenin model as shown in Fig. 3. The chip can use the entire power available at antenna if a perfect impedance matching is performed [18] with consideration of the Φ function. Therefore, the antenna impedance must be conjugate of the chip one.

As mentioned in [19], for a metallic antenna immersed in an infinite uniform medium with a relative permittivity ε_r, the input impedance is defined as:

$$Z_a(f;\varepsilon=\varepsilon_r) = Z_a(f\sqrt{\varepsilon_r};\varepsilon=\varepsilon_0)/\sqrt{\varepsilon_r} \tag{1}$$

Thus, the antenna input impedance at frequency f, when embedded in a dielectric medium with relative permittivity ε_r, is equal to its impedance at frequency $f\sqrt{\varepsilon_r}$ scaled by $\sqrt{\varepsilon_r}$.

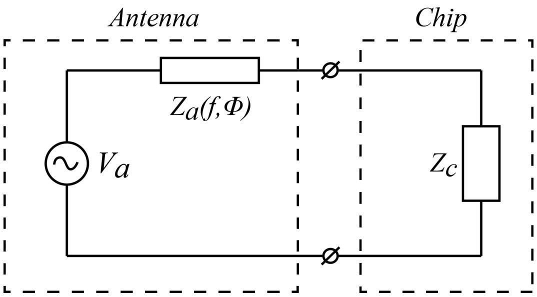


Figure 3: Equivalent circuit model of passive RFID tag

With regard to automotive tire case, the tag may be immersed in rubber with finite thickness having $\varepsilon_r = 6.1$. As noted in [20, 21] we will consider the effective permittivity of the rubber media defined as:

$$\varepsilon_e = (\varepsilon_r + 1)/2 \tag{2}$$

Therefore the complex power reflection coefficient Γ, when tag antenna is immersed in a dielectric media, can be defined as:

$$\Gamma = (Z_c - Z_a^*(f;\varepsilon_e))/(Z_c + Z_a(f;\varepsilon_e)) \tag{3}$$

$$\Gamma = (Z_c\sqrt{\varepsilon_e} - Z_a^*(f\sqrt{\varepsilon_e};\varepsilon_0))/(Z_c\sqrt{\varepsilon_e} + Z_a(f\sqrt{\varepsilon_e};\varepsilon_0)) \tag{4}$$

In order to deliver the maximum power available at antenna (considered as source) to the chip (considered as load), the power reflection coefficient Γ should be null thus: $\Gamma = 0 \Leftrightarrow R_c\sqrt{\varepsilon_e} = R_a(f\sqrt{\varepsilon_e};\varepsilon_0)$ and $X_c\sqrt{\epsilon_e} = -X_a(f\sqrt{\varepsilon_e};\varepsilon_0)$

Let us consider that the operation frequency is f and the ASIC chip impedance, at this frequency, is $Z_c(f) = R_c(f) + jX_c(f)$. Hence, the antenna should be designed to work at $f\sqrt{\varepsilon_e}$ frequency and to be matched to an impedance equal to $\sqrt{\varepsilon_e}R_c(f) + j\sqrt{\varepsilon_e}X_c(f)$ in order to avoid the mismatch effects once the tag is embedded in the working medium.

Then the power reflection coefficient can be calculated by:

$$\Gamma^2 = |(Z_c - Z_a^*(f;\varepsilon_e))/(Z_c + Z_a(f;\varepsilon_e))|^2 \tag{5}$$

More specifically, the power transmission coefficient, τ, can be defined as:

$$P_c = \tau P_a \tag{6}$$

Where P_a stands for the power collected by the tag antenna and P_c refers to the power at the chip. We can also express the power transmission coefficient τ by:

$$\tau = 1 - \Gamma^2 \tag{7}$$

By using Eq.(5) and Eq.(7), the power transmission coefficient can be expressed in terms of impedances by:

$$\tau = (4R_a(f\sqrt{\varepsilon_e}; \varepsilon = \varepsilon_0)\sqrt{\varepsilon_e}R_c) / \left|Z_a(f\sqrt{\varepsilon_e}; \varepsilon = \varepsilon_0) + \sqrt{\varepsilon_e}Z_c\right|^2 \tag{8}$$

This approach model can help designers to conceive RFID antenna that works correctly when embedded in any dielectric medium. Hence, we can deal with mismatch effects caused by the surrounding environment. In general, the ASIC chip used in RFID tag has an important negative imaginary part and a small real part [15]. We can admit that the chip has a capacitive behavior in order to store energy. Hence, the designed antenna should have an inductive behavior in order to minimize the reflection coefficient Γ and maximize the amount of power delivered to the ASIC chip.

2.3. Read Range

To wake up the tag, in most RFID scenarios, the reader interrogates the tag by sending a query signal. Hence, the RFID tag should be present in the vicinity. Now, we can talk about read range. This latter is the maximum distance at which RFID tag can notice a minimum power from reader signal and the tag can deliver necessary information to the base station [17]. Therefore, we can consider two distances one in uplink and another in downlink. The read range is the smaller of these two distances because tag sensitivity is generally low [18]. The read range depends also on propagation conditions, tag antenna polarization and material of tagged Item [18].

By using Friis formula, the read range r can be calculated as:

$$r = (\lambda/4\pi)\sqrt{P_t G_t G_r \tau / P_{th}} \tag{9}$$

Where λ is the wavelength, P_t is the power transmitted by the reader, G_t is the gain of the reader antenna (transmitter), G_r is the gain of the tag antenna (receiver), P_{th} is the minimum threshold power necessary to turn on the RFID tag chip and τ is the power transmission coefficient.

We have to notice that the impedance match condition ($\Gamma = 0$) enhances the performances of tag antenna, particularly the read range. With a view to increasing the read range, the impedance matching should be perfectly performed.

A set of requirements must be considered while designing an RFID tag antenna. The designer can deal between antenna gain, impedance matching, and bandwidth [18].

2.4. Tag Antenna Design

Our proposed design is based on our approach and recommendations described in [18]. The tag has been designed to be immersed in automotive tire in order to collect their inventory information and physical conditions (pressure, temperature, stress, road conditions etc). Furthermore, sensors may be included with tags. Then the tag can communicate with reader within an operation frequency.

We opted for the $902 - 928MHz$ band. We selected the $915MHz$ as operating frequency for our tag antenna. To reduce the cost and have a straightforward fabrication, the antenna trace is made of copper with a thickness $T_a = 0.018mm$ and trace width $W = 0.8mm$.

For our application, we chose the NXP UCODE G2XL chip [22] with TSSOP8 packaging. The integrated chip (IC) exhibits a complex impedance $Z_c = 16 - j148$ at $915MHz$ frequency. It has a low resistance part and a relatively high reactance part.

The Fig. 4 shows the shape and the structure of our proposed RFID tag antenna. In order to reduce the antenna size and having a low profile, meandered line antenna (MLA) was performed. Meandering allowed the antenna to be compact and to provide omnidirectional radiation. As shown in Fig. 4, the antenna is designed with a nonuniform MLA (NU-MLA) in order to increase the gain [14].

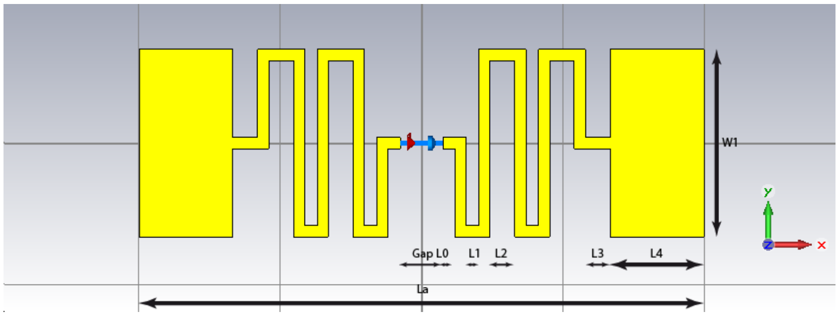


Figure 4: Structure of our proposed RFID Antenna

Most of passive RFID tag antenna suffers from narrowed bandwidth. So to deal with this problem, we decided to add a square patch at the ends of the meander line. Hence, we can talk about end-loaded antenna [23].

The proposed antenna geometry is optimized to be directly connected with the NXP UCODE G2XL chip. The numerical study led us to evaluate the proposed antenna geometry in free space and when embedded in rubber layer, with a highly dielectric permittivity and thickness, in order to illustrate tire material effects.

3. Results and Discussion

We aim to embed the tag in tire's sidewall that has $\varepsilon_R ubber = 6.1$ according to [16] study. With a view to validating our approach, we simulated the tag antenna in two different mediums: in free space and in rubber material. The piece of rubber has the following dimensions: length $L_r ub = 87mm$, width $W_r ub = 87mm$ and thickness $T_r ub = 10mm$. Fig. 5 depicts the simulated S11 parameter of both cases. We can notice that rubber medium affects the antenna input impedance and then changes the resonance frequency. It is observed that resonance response is perfectly achieved even tag antenna is placed in free space or when embedded in rubber material ($f_{FreeSpace}$ = 1724MHz for free space and f_{Rubber} = 915MHz in rubber tire). As shown in Fig. 5, the resonance frequency is shifted down drastically due to this highly dielectric material, but it still tuned to the ASIC chip. With regards to dielectric medium our approach may be helpful to expect the influences of these mediums. Therefore antenna designer can avoid mismatch effects caused by dielectric medium once antenna is embedded into. Table I gives the optimized dimensions of the proposed tag antenna.

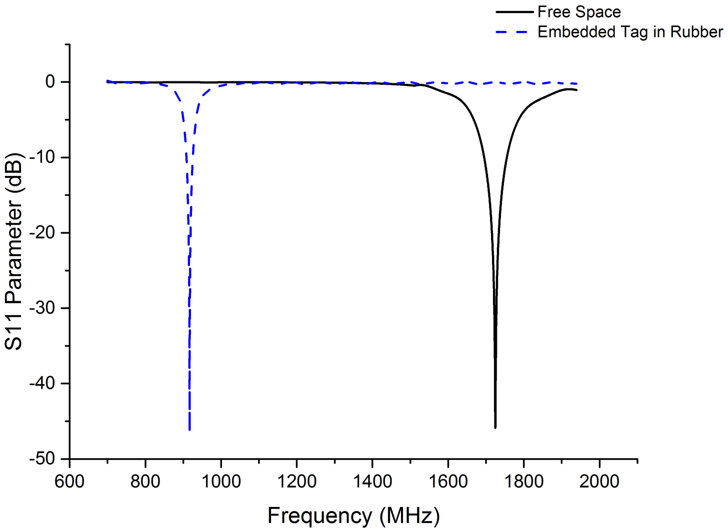


Figure 5: S11 parameter for both cases, Free Space and Rubber Material

As illustrated in Fig. 5. The magnitude of the reflection coefficient is below $-46dB$ at the desired frequency $915MHz$. We can affirm that the integrated chip receive the maximum power available at the proposed tag antenna

Table 1: OPTIMIZED DIMENSIONS OF THE PROPOSED ANTENNA IN MM

Dimension	Value	Dimension	Value	Dimension	Value
L0	0.87	W1	13.25	Ta	0.018
L1	0.87	W	0.8	Trub	10
L2	1.74	Wrub	87	L4	6.625
L3	1.74	Lrub	87	Gap	3

even immersed in dielectric rubber. Therefore, the antenna impedance is conjugated properly to the ASIC one. Fig. 6 shows its input impedance that is $Z_a = 16.13 + j148.04$. Having proper impedance matching could ensure a longer antenna reading distance, which is a paramount important requirement for RFID application.

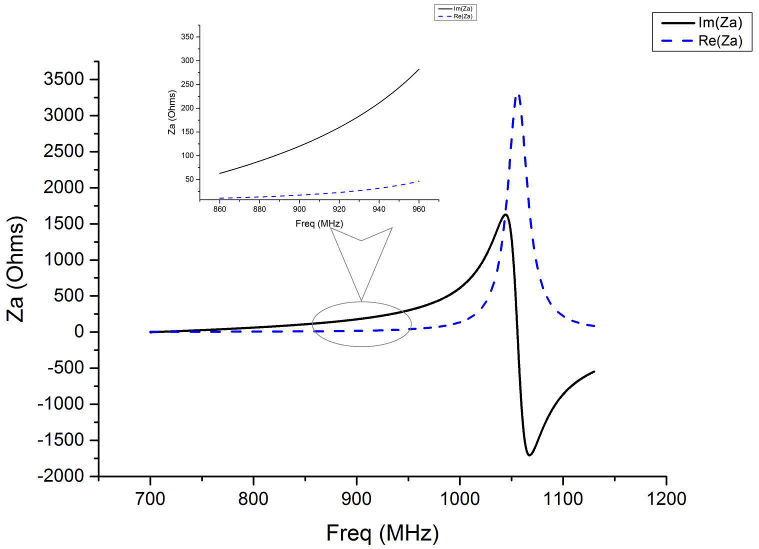


Figure 6: Antenna Input Impedance

Usually for RFID system, the impedance bandwidth is calculated for $S11$ under $-10dB$. From Fig. 5 we can observe that the impedance bandwidth is reduced when tag is embedded in rubber. For our case, the simulated impedance bandwidth is $17.26MHz$. It is included in the allowed bandwidth in North America (902 - 928 MHz). The most RFID tag antenna suffer from narrowed bandwidth [14]. Hence, the proposed antenna has significant advantage in bandwidth aspect.

To investigate the effect of the square patch added at antenna's ends, we have simulated the reflection coefficient for different sizes of the square. Fig. 7 illustrates Γ for different widths and its height is set to 13.25 mm. In Fig. 8, we depict Γ for different heights and the width is set to 6.625 mm. It is worth noting that resonance frequency is shifted down when the square's height is increased. We can also notice that the magnitude of the S11-parameter is below $-35dB$ while the resonance frequency is shifted down. In fig. 7, it is observed that the resonance frequency is shifted down while the square's length increases.

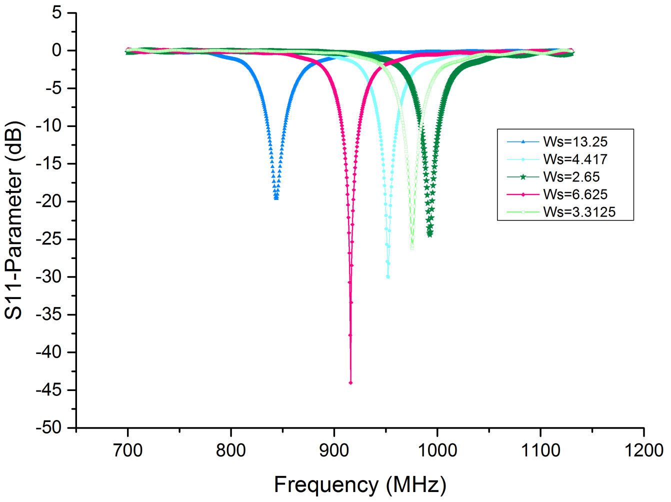


Figure 7: Reflection coefficient for different widths. Ws stands for square's width

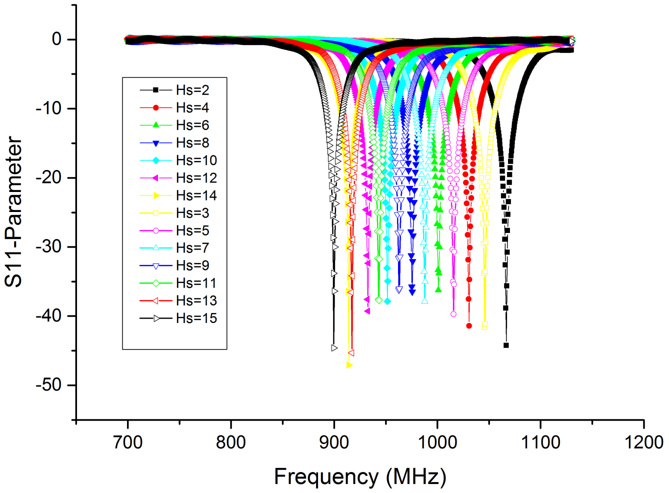


Figure 8: Reflection coefficient for different heights. Hs stands for square's height

Fig. 9 illustrates the simulated gain. The proposed tag antenna exhibits a maximum gain over θ plane. As shown in Fig. 10, the maximum obtained gain is $1.31dB$ at the operation frequency. Compared to uniform MLA studied in [14], our tag antenna can provide considerable result in gain characteristic. The gain is a little bit higher when simulated in free space ($G_{ant}{}^{FreeSpace} = 1.67dB$)

From the radiation patterns, the proposed antenna exhibits omnidirectional radiation. As depicted in Fig. 7, its maximum directivity is 1.87 dBi with $-0.57dB$ total efficiency at desired frequency when $\theta = \Phi = 90^\circ$. The radiation efficiency η is about 87.73 percent. Due to its omnidirectional radiation characteristic, the tag can notice the radiated power from RFID reader even if it is placed in any position and angle.

Our proposed antenna, based on our approach, offers an important gain compared to the antenna studied in [24]. Besides, its overall size ($40mm *$

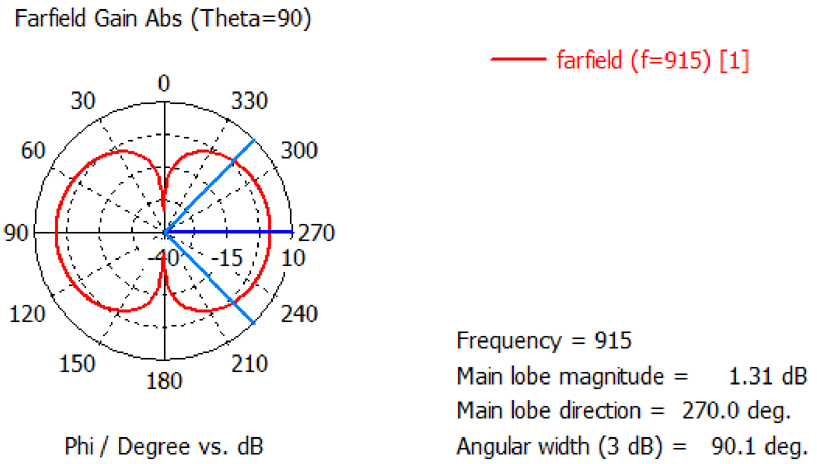
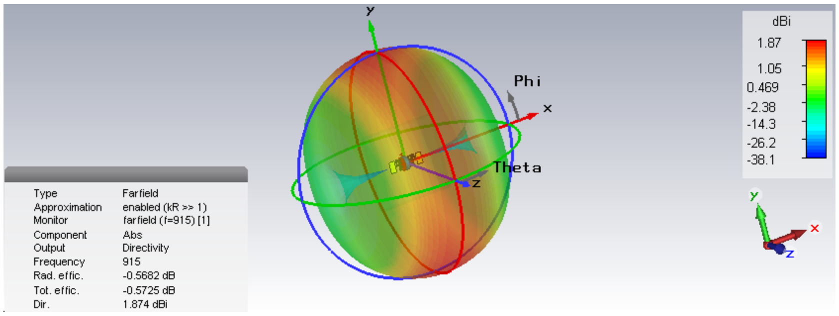


Figure 9: Simulated 2D-Gain



Type	Farfield
Approximation	enabled (kR >> 1)
Monitor	farfield (f=915) [1]
Component	Abs
Output	Directivity
Frequency	915
Rad. effic.	-0.5682 dB
Tot. effic.	-0.5725 dB
Dir.	1.874 dBi

Figure 10: Simulated 3D-directivity

$13.5mm$) is very compact and it has a low profile than those proposed in [25, 26].

4. Conclusion

A novel passive RFID tag antenna for automotive tire was proposed. The simulation results prove that our designed antenna will ensure good performances for automotive tire application and it can be a good candidate for RFID system. The meandering technique was a helpful solution to reduce the antenna size. The proposed approach was a efficient solution to predict the matching parameters when tag is embedded in rubber tire with high dielectric permittivity in order to maximize power delivered to ASIC chip. That is useful to increase read distance too. The end-loading square patch improves the impedance bandwidth and radiation.

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