UHF-HF RFID Integrated Transponder for Moving Vehicle Identification

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Abstract **—** This paper presents a passive HF-UHF RFID integrated transponder for the identification of a moving vehicle. It consists of a single ISO 7810 ID-1 Card where both a UHF meander dipole antenna and an ISO 15693 commercial tag are arranged. The UHF antenna is designed by using a parametric analysis of the optimal shape of the meanders to obtain a proper conjugate matching between the antenna and the RFID microchip. A single-lane identification scenario is presented and simulated. The effects of the electromagnetic reflection and diffraction on the reading range as well as on the identification operations of a tagged vehicle are also investigated. Numerical simulations and experimental results on a prototype of the conduced transponder confirm the possibility of using this technology for the identification of a moving vehicle approaching a road-toll system with a relatively slow speed.

Index Terms **—** RFID, UHF tag, HF tag, integrated transponder, moving vehicle.

I. INTRODUCTION

Radio Frequency Identification (RFID) is a recent outstanding technology which permits the identification and tracking of objects by using wireless data exchange between a reader station and small transponders or tags located on the objects to be identified [1]. Typically these RFID tags are composed of an integrated microchip and an electromagnetic coupling element or antenna. The identification process takes place through an RFID reader which interrogates a specific volume and collects information about the objects, exchanging wireless data with the object's tags located in the mentioned volume. RFID systems may be active or passive depending on whether the tags have their own power supply.

RFID systems operating at HF band (13.56 MHz) are widely used in the areas of ticketing, personnel access control and object tracking. These systems employ the near field inductive coupling to transfer energy and binary data between the reader and the tags. They are characterized by an excellent immunity to environmental noise and electrical interference and exhibit a minimal shielding effect from adjacent objects and human body. However, limits are imposed on the permitted magnetic field strength due to country regulations. This limitation has resulted in the maximum achievable reading range of approximately 1 m.

RFID systems operating at higher frequencies, especially at the UHF band, allowing us to obtain middle to long range wireless links combined with good reliability of the communication. Passive RFID systems at UHF (865-868 MHz in Europe, 902-928 MHz in North and South America and 950-956 MHz in Japan) and microwave (2.45 GHz) bands use the modulated scattered technique to establish a radio link between the reader and the tags. Here, the reflected signal from the tag is modulated by an integrated microchip (IC) directly connected to the antenna. As a consequence, RFID transponder performances are strongly affected by the frequency-dependent impedance match between antenna and IC. However, in these frequency ranges it is possible to resort to antennas

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with far smaller dimensions and greater efficiency than that employed at frequency ranges below 30 MHz. Depending on the IC sensitivity and on the tag antenna performances, typical ranges of 4-6 m can now be achieved using passive UHF backscatter transponders. Typical applications of these RFID systems are in logistic as well as access control services.

The continuous growing of the market demand has promoted intense research on RFID systems for non conventional applications. Among which significant efforts have been made in developing RFID tags and intelligent transponders for vehicle to road-side communications to automate vehicular control access and road-tolling operations [2, [3]. Moving vehicles are typically identified by active tags due to their largely extended communication range and high operational efficiency [4]. However, the use of active tags presents some impairments, such as the high cost for mass production when compared to passive ones, and the life expectancy of the battery. Moreover, the long reading distance may cause some problems in controlling the reader detection volume, which may result in possible wrong detections by the reader when it operates in a multi-lane identification environment. The use of passive tags is more advantageous due to their low cost, compactness and maintenance free nature.

This paper presents and analyzes an RFID passive integrated HF-UHF tag for the identification of moving vehicles within a mono-lane scenario. It is found that this type of transponder may be used in all the multi-service applications where a high level of interoperability between different systems is required [5], [6]. The integrated UHF-HF RFID passive tag is composed of a UHF meander dipole antenna operating at the European band (865-870 MHz) and an HF (13.56 MHz) ISO 15693 commercial tag arranged in two separate sections on an equivalent ISO 7810 ID-1 card space. The UHF antenna has been designed to provide small size and proper conjugate matching to the high-capacitive input impedance of the tag IC. The antenna design has been optimized, taking into account both the presence of the commercial ISO 15693 tag located in the HF section and the presence of the car windshield. UHF antenna characteristics, including both the return loss with respect to the IC input impedance and radiation pattern, are investigated. In order to assess the effects of the various reflection and diffraction contributions originated by the presence of the car body, which may reach the passive tag, a single-lane vehicle identification scenario is also simulated and analyzed. It is found that in some conditions the presence of multiple paths tends to enhance the minimum field intensity required to activate a passive tag, thus improving the achievable reading distance. Finally, a prototype of the integrated transponder printed on FR4 substrate has been developed and tested in a real scenario. Experimental tests have shown a good overall performance of the transponder, and have confirmed a possible increase of the tag performances in terms of reading distance in presence of the car body.

II. TRANSPONDER STRUCTURE

One of the main challenges of this work is to accommodate two different passive tags operating at HF and UHF bands, with their own radiating structures on a single ISO 7810 ID-1 Card . Typical dimensions of an ISO 7810 ID-1 Card are 85.72 x 54.03 mm which also represent the space available to integrate the two tags. During the design process, it is essential to find the best tradeoff between the space occupied by the tags and the desired operational requirements. Moreover, the final layout has to satisfy the typical RFID requirements in terms of flexibility and low cost for mass production. The above requirements can be achieved by designing a UHF uniplanar single-layered dipole-type antenna with reduced size to take advantage of the common PCB techniques as well as the low cost. In addition, to improve the transponder performance, a correct conjugate impedance matching between antenna and tag IC has to be obtained. Passive ICs are intrinsically highly reactive because of the necessary power to bias the IC front-end, which is delivered through electromagnetic coupling. In this case, due to the low input resistance and the relatively high capacitive reactance of the IC, antennas with a low resistive and highly inductive input impedance have to be designed to achieve a conjugate match the IC. A simple way to reduce the size of a dipole antenna and to obtain both a relatively high inductive input impedance and reliable radiation characteristics is to resort to a T-match dipole antenna with meandered arms [5],[7],[8]. The antenna layout is shown in Fig. 1

where the geometrical parameters of the antenna are also indicated.

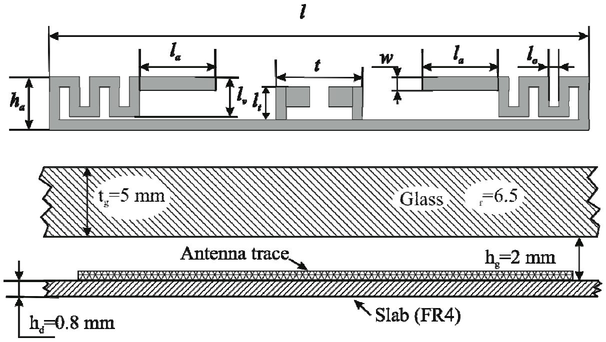

Fig. 1. UHF tag antenna layout and simulation model.

The RFID chip chosen to connect to the prototype antenna is a UHF Gen2 Strap kindly provided by Texas, with an estimated packaged chip input impedance of $Z_c = (11 - j63)\ \Omega$ and a power sensitivity $P_{th} =$ -13 dBm at $f = 867$ MHz.

In RFID systems operating at HF band (13.56 MHz), the tag coupling element is typically constituted by a planar coil antenna that may be built at low cost using etching or common screen printing technique. Concerning the HF section, due the wide availability of commercial inlays, we chose to resort to a commercial ISO 15693 Tag constituted by a copper wire deposited antenna coil connected to a Philips I-Code RFID chip. This commercial Tag is 52 mm x 41 mm thus leaving an available space of about 81 mm x 12 mm for the UHF antenna. However, to take into account the presence of the HF antenna coil while designing the UHF tag, a 6-turn rectangular loop coil is considered in the numerical simulations, as illustrated in Fig. 2. The prototype transponder has been derived on a single grounded low cost FR4 dielectric slab ($\varepsilon_r = 4.4$, $h = 0.8$ mm) and has been design to operate at the European licensed UHF band (center frequency $f = 867$ MHz). The proposed arrangement provides a satisfactory overall tag performance with respect to other conceivable layouts.

III. UHF ANTENNA DESIGN AND ANALYSIS

The UHF antenna has been designed and optimized using a commercial electromagnetic simulation software. The main goal of the design has been to tune the antenna input impedance in such a way to be the conjugate of the microchip characteristic impedance when the tag is in the operative environment. Numerical simulations are first carried out by modeling the presence of the car windshield near the tag antenna. The glass has been modeled as a planar dielectric layer of thickness $t_g = 5$ mm, with relative dielectric permittivity $\varepsilon_r = 6.5$ located at a distance $h_g = 2$ mm from the antenna, as shown in the second part of Fig. 1.

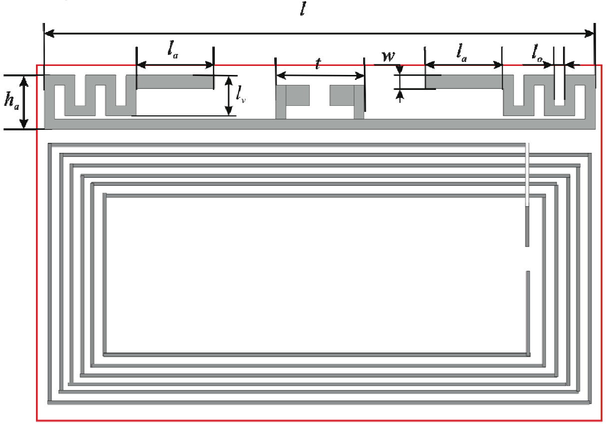

Fig. 2. UHF-HF integrated transponder layout.

A. Return Loss

As mentioned above, a proper impedance match between the antenna and the IC is very important in order to maximize the tag performances. In RFID tags, the antenna is directly connected to the chip, which typically exhibits a high-capacitive input impedance. To obtain a better conjugate impedance match, it is important to minimize the Kurokawa's power reflection coefficient $|s|^2$ [9], [10], where s is defined by

$$s = \frac{Z_c - Z_a^*}{Z_c + Z_a} \tag{1}$$

where Z_a is the complex antenna impedance and Z_c is the complex IC input impedance. The maximum reading range $D_{\max}$ of an RFID system is directly affected by the power reflection coefficient and can be computed using the Friis free-space formula as

$$D_{max} = \frac{\lambda}{4\pi}\sqrt{\frac{P_{erp} G_r}{P_{th}} p(1-|s|^2)} \tag{2}$$

where λ is the wavelength, P_{eirp} is the equivalent isotropic radiated power transmitted by the reader, G_r is the tag antenna gain, P_{th} is the minimum power required to activate the chip, and p is the polarization loss factor.

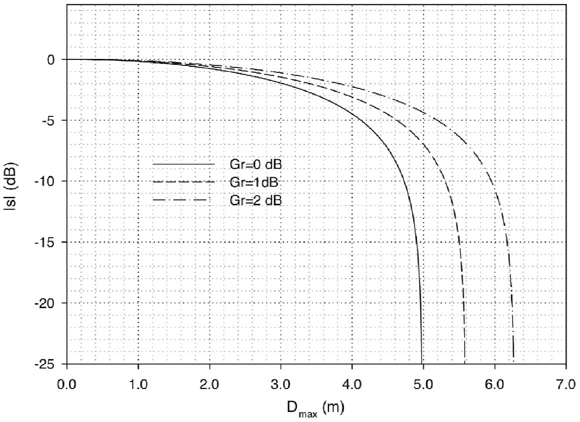

Fig. 3. Return loss as a function of the maximum achievable reading range for different tag antenna gain ($P_{th} = -13$ dBm, $p = 0.5$, $f = 867$ MHz, P_{eirp} = 35.16 dBm).

In Fig. 3 the return loss as a function of the maximum achievable reading range, for a given antenna gain G_r, is reported. Calculations are made for a chip sensitivity $P_{th} = -13$ dBm, frequency $f = 867$ MHz, polarization loss factor $p = 0.5$, and for the maximum allowed P_{eirp} by the European regulations (P_{eirp} = 35.16 dBm). It is shown that for a given EIRP tag antenna gain, the reading range may not be significantly increased by increasing the return loss over about -15dB to -17dB. These return loss values can be considered as the impedance match requirements in order to obtain good tag performance.

Among all the geometrical parameters considered in the design process, the key ones are the vertical l_v and the horizontal l_o length of the meander line branches, as well as the length l_a of the final arms. As is well known, the length of a resonating dipole must be approximately half of the wavelength at the operational frequency. The geometrical dimensions of the T-match, which comprise the two parameters t and l_t, have been dictated by the size of the chip pads. As a first step, the design parameters were set such that the total length of the dipole measured at the median line was half wavelength at $f = 867$ MHz, provided that the dipole could fit the space available for the UHF section. The length of the final arm l_a was initially chosen between the maximum and minimum values feasible. This allows us to tune the antenna around the desired frequency. A capacitor connected in series to the feeding port of the antenna has been used in the simulations to take into account the capacitive part of the microchip impedance. Concerning the shape of the meanders, there is not a unique choice for l_v and l_o. To better select these values, once the total length of the dipole is fixed, we analyzed the behavior of the antenna input impedance for several ratios $\eta = l_v / l_o$. Figures 4 and 5 show the impedance curves for different values of η.

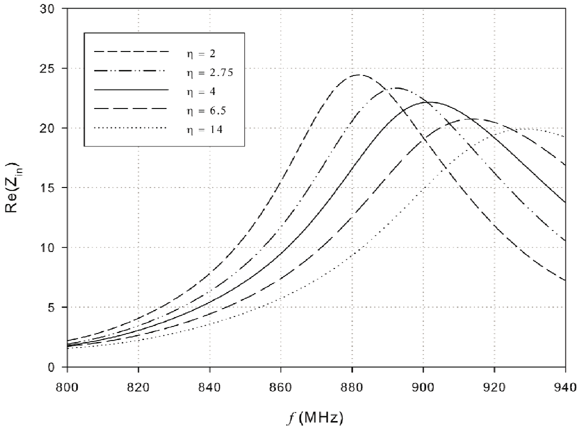

Fig. 4. Real part of the antenna input impedance for different values of $\eta = l_v / l_o$.

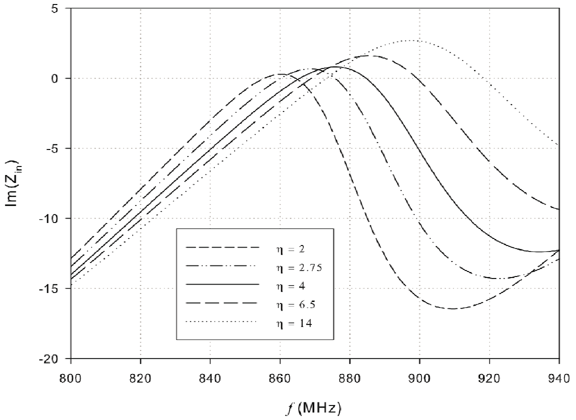

Fig. 5. Imaginary part of the antenna input impedance for different values of $\eta = l_v / l_o$.

In Fig. 5 we can observe that for every value of η considered in the simulations the dipole is almost resonant within the band of interest, since the imaginary part of the impedance is vanishing. This is because the resonant frequency mostly depends on the length of the dipole, which is kept constant. From Fig. 4 we notice that for $\eta = 4$, the antenna impedance exhibits a real part of about 11 Ω at $f = 865$ MHz, thus suggesting a good conjugate matching between antenna and microchip impedance at that frequency. The frequency shift between this result and the initial guess is mainly due to the T-match feeding, since the T-match can modify the electrical length of the dipole. In the last step, the fine tuning to the frequency $f = 867$ MHz can be achieved by modifying the length l_a of the final arms of the dipole without significantly changing the impedance matching between antenna and microchip. The final geometrical dimensions of the meandered dipole antenna are $w = 1.5$ mm, $l = 81$ mm, $h_a = 8$ mm, $l_o = 1.5$ mm, $l_a = 11$ mm, $l_v = 6$ mm, $l_t = 5$ mm, $t = 13.24$ mm.

In Fig. 6, the magnitude of the input reflection coefficient is reported. For this antenna, the -10dB bandwidth is approximately 45 MHz, due to the low input impedance quality factor of the IC (~ 5.8).

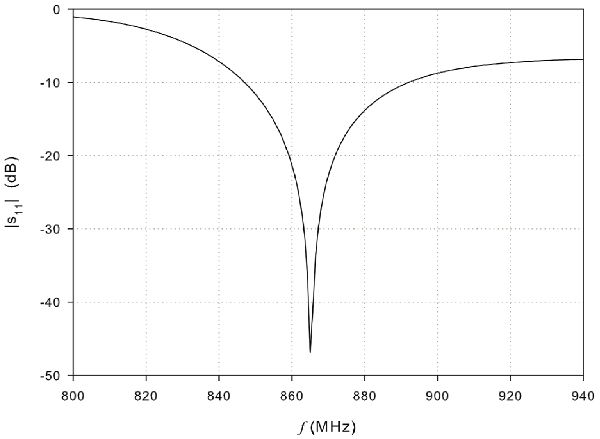

Fig. 6. Antenna input reflection coefficient.

B. Radiation Pattern

The simulated E- and H-plane radiation patterns at $f = 867$ MHz of the co-polar components for the proposed antenna in the final configuration are shown in Fig. 7. These curves show that the obtained radiation patterns are somewhat similar to that of a typical dipole. It is also observed that the maximum of the radiation pattern in the H-plane plane is slightly tilted towards the side where the HF coil antenna is located. However it is expected that this effect does not significantly influence the overall performance of the transponder in the direction perpendicular to the dipole plane. Simulations have also shown about 1.5 dB antenna gain at the working frequency.

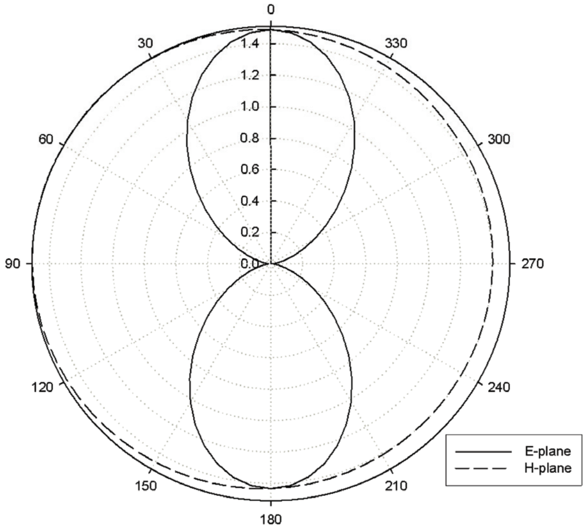

Fig. 7. E-plane (continuous line) and H-plane (dashed line) radiation patterns at 867 MHz.

IV. SINGLE-LANE VEHICLE IDENTIFICATION SCENARIO

In operative conditions the identification of a moving vehicle can be difficult because of multiple path signals that may reach the passive tag during the interrogating operations. Multiple paths are mainly due to reflections and diffractions that occur at the metallic surfaces and edges of the car body. In particular, it is expected that the dominant phenomena are associated with the reflection from the hood of the car and with the diffractions at the surrounding metallic edges of the windshield. To estimate the amount of these interferences and their effects on the performances of the passive tag when located on the windshield of a car, a single-lane identification scenario has been conceived and implemented using a commercial numerical code (Feko). The model implemented consists of a part of the metallic car body with a planar glass windshield illuminated by a circularly polarized patch antenna operating at 867 MHz, as illustrated in Fig. 8. The antenna is centered with respect to the lane width and the height over the lane is $h_a = 5.5\,\mathrm{m}$. The beam axis of the antenna is tilted from the horizontal by a $\theta_a = 60°$ angle. The transmitted ERP of the antenna has been set to 2W and, taking into account all the other parameters, the activating electric field intensity for the chosen chip is about 2.5 V/m. In order to limit the computational burden, the car model is constituted of solely the parts that contribute to the reflected or diffracted field at the tag position, as illustrated in Fig. 8. The windshield of the car is modeled by a planar glass of thickness $t_g = 5\,\mathrm{mm}$ and dielectric permittivity $\varepsilon_r = 6.5$. The total electric field has been observed on a rectangular plane located inside the car parallel to the windshield at a distance of about 2 mm. By symmetry the observation plane is taken to be half of the windshield, with the origin of the x-axis corresponding to the centre of the lower-edge of the windshield and marching towards the lateral edge of the windshield on the x-axis.

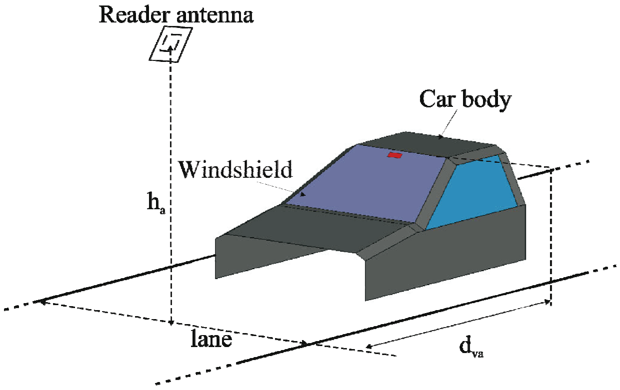

Fig. 8. Simulated single-lane vehicle identification scenario.

As an example, the simulated total electric field intensity at the observation plane for a distance $d_{va} = 2\,\mathrm{m}$ has been reported in Figs. 9 and 10.

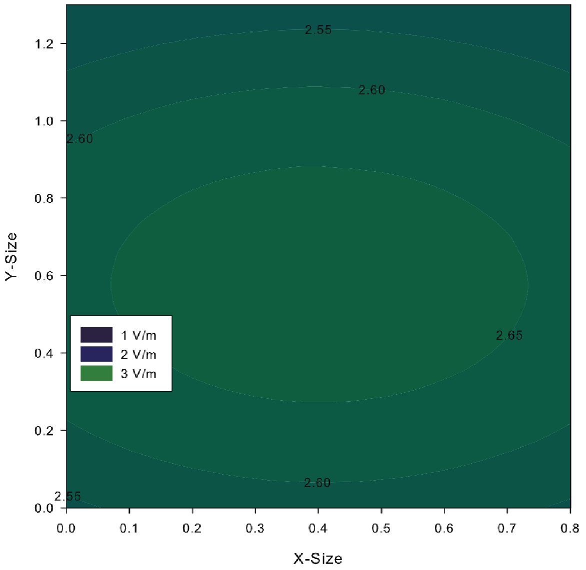

Fig. 9. Electric field intensity at the observation plane without the car body.

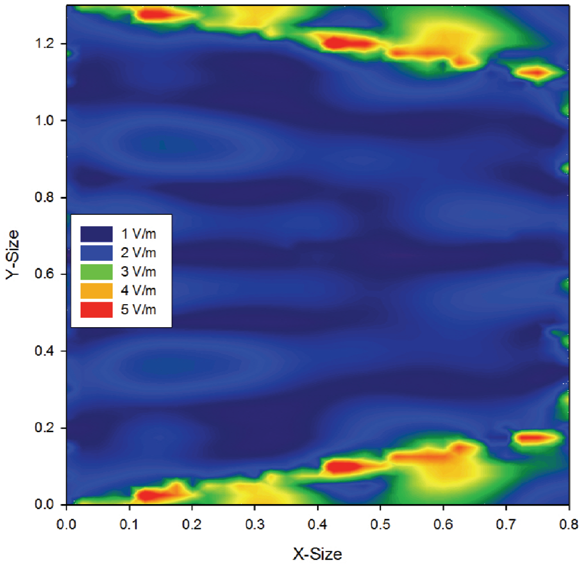

Fig. 10. Electric field intensity (V/m) at the observation plane in presence of the car body.

The case of free space, where both the car and lane are not present, is shown in Fig. 9. It is observed that the field footprint is dictated by the radiation pattern of the antenna, and that the field intensity in the most part of the windshield is very close to the activation threshold. A completely different situation is shown Fig. 10 where the car body is present.

It is shown that diffractions and reflections by the car body can cause an enhancement of the field intensity in regions near the upper portion of the glass. In these parts of the windshield the total electric field intensity may be significantly higher than the activation threshold. Moreover, due to the particular geometry configuration, these effects tend to remain rather constant also when the car is moving inside the beam footprint. As a result, the physical gate useful for radio communications that is created with the combination of these effects can be quite large and permits the implementation of a non-stop tolling system.

V. EXPERIMENTAL RESULTS

A prototype of the integrated transponder at the European band ($f_o = 867$ MHz) with the proposed antenna has been built using FR4 ($\varepsilon_r = 4.4$, thickness $h = 0.8$ mm) as a substrate and copper for the traces.

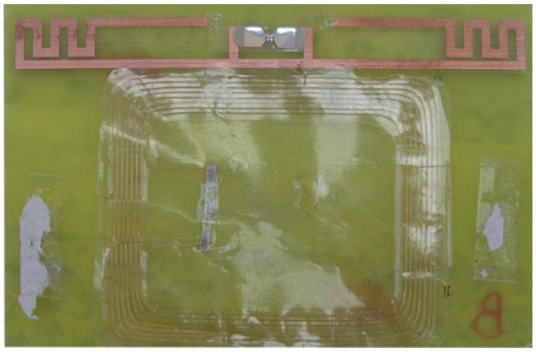

Fig. 11. Prototype of the integrated transponder.

A picture of the prototype is shown in Fig. 11. As mentioned above, the commercial ISO 15693 Tag consists of a copper wire antenna coil deposited on a plastic flexible substrate, which can be easily placed next to the UHF tag antenna. The reading range for the tag has been measured by using a setup composed of a UHF Reader and circularly polarized antenna with gain $G_t = 9$ dBc.

In order to test the maximum reading range of the integrated transponder when placed on the windshield, the reader antenna was first positioned in front of the car under test, such that the tag was illuminated directly by the reader antenna beam. Table 1 shows the measured maximum reading distance of the UHF tag of the integrated transponder when it is equipped with the HF tag.

Table 1: Maximum reading distance.

	Position A	**Position B**
Car type 1	9.1 m	8.5 m
Car type 2	7.6 m	8.9 m

Test results have been obtained for two different types of car and two different positions of the transponder on the windshield. The two positions A and B refer to an upper central and upper lateral position of the transponder on the windshield, respectively, and are illustrated in Fig. 12.

(a) Upper central position (A)

(b) Upper central position (B)

Fig. 12. Tag position on the windshield during the tests.

It is found that the maximum reading distance is significantly higher than the one expected in free space, thus substantiating an enhancement of the field intensity near the glass-metal junction of the windshield. An uninterrupted reading capability is observed when reducing the distance as the vehicle moves. The measurements show that the presence of the HF coil does not significantly degrade the tag performance. Finally, preliminary tests have also been conducted in a real scenario to establish the number of times a vehicle is identified while approaching a portal-frame equipped with an overhead reader set-up. Test results show that the car type 1 equipped with the proposed tag in position A can be identified al least 2 times, up to a vehicle speed of about 40 Km/h.

VI. CONCLUSION

In this paper an RFID passive integrated HF-UHF tags for the identification of moving vehicles within a mono-lane system for road-toll operations has been presented and analyzed. The passive transponder operates within the European band (865-870 MHZ) and it consists of both a UHF tag and an ISO 15693 commercial tag, arranged in two separate sections on a single ISO 7810 ID-1 card. A design process of the UHF tag antenna which allowed us to obtain a relatively small antenna with proper conjugate matching to the capacitive input impedance of the chosen tag IC has been presented. Simulation results have shown an antenna gain of about 1.5 dB and a power reflection coefficient with a -10 dB bandwidth of about 45 MHz. The radiation patterns produced by the simulations agree with the ones of a typical planar dipole antenna. A single-lane identification scenario has also been conceived and simulated, with the aim of analyzing the effects of the various reflection and diffraction phenomena originating at the car body on the identification operations. Simulation results have shown that, for the chosen configuration of the set-up, multiple path phenomena may cause an enhancement of the field intensity near the upper glass-metal junction of the windshield. This phenomenon may be used to obtain a reading zone useful for the identification of a moving vehicle approaching a road-toll system with a relatively slow speed. A prototype of the integrated transponder has been built and tested in a real scenario. Test results have confirmed the good performance of the integrated transponder and have shown an uninterrupted identification capability of a tagged-car up to distances greater then the ones expected for a free space scenario.

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REFERENCES

[1] K. Finkenzeller, *RFID Handbook,* Wiley & Sons, Second Edition, 2003.

[2] D. L. Almanza-Ojeda, A. Hernandez-Gutierrez, and M. A. Ibarra-Manzano, "Design and implementation of a vehicular access control using RFID," *Multiconference on Electronics and Photonics (MEP* 2006), Guanajuato, Mexico, pp. 223-225, 2006.

[3] A. G. Foina, S. E. Barbin, and F. J. Ramirez, "A new approach for vehicle access control using active rfid tags," *SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference, IMOC 2007,* pp. 90-93, 2007.

[4] P. Blythe, "RFID for road tolling, road-use pricing and vehicle access control," *IEE Colloquium on RFID Technology,* pp. 8/1-8/16, 1999.

[5] A. Toccafondi and P. Braconi, "Compact meander line antenna for hf-uhf tag integration," *Proc. of IEEE AP-Symposium,* June 2007.

[6] M Hirvonen, N. Pesonen, O. Vermesan, C. Rusu, and P. Enoksson, "Multi-system, multi-band rfid antenna: Bridging the gap between hf- and uhf-based rfid applications," *European Conference on Wireless Technology,* pp. 346-349, 2008.

[7] G. Marrocco, "Gain-optimized self-resonant meandered line antennas for RFID applications," *IEEE Antennas and Wireless Propagation Letters*, vol. 2, pp. 302--305, 2003.

[8] K. V. Seshagiri Rao, P. V. Nikitin, and S. F. Lam, "Antenna design for UHF-RFID tags: a review and a practical application," *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 12, pp. 3870-3876, Dec. 2005.

[9] K. Kurokawa, "Power waves and the scattering matrix," *IEEE Transactions on Microwave Theory and Techniques*, vol. 13, no. 3, pp. 194-202, Mar. 1965.

[10] P. V. Nikitin, K. V. S.Rao, S. F. Lam, V. Pillai, R. Martinez, and H. Heinrich, "Power reflection coefficent analysis for complex impedance in RFID tag design," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 9, pp. 2721-2725, Sept. 2005.

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