Research Journal of Applied Sciences, Engineering and Technology 6(12): 2118-2126, 2013
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: December 3, 2012 Accepted: January 17, 2013 Published: July 30, 2013

Design and Development of a Compact Wideband C-Shaped Patch Antenna for UHF RFID Tag

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Abstract: A compact low profile patch antenna for Ultra-High Frequency (UHF) Radio Frequency Identification (RFID) tag for metallic applications is presented in this research study. By employing two gap-coupled C-shaped patches, wide half-power impedance bandwidth (RL $\geq$3 dB) of 152 MHz is achieved for universal application UHF (860-960 MHz) RFID. Moreover, the proposed patch antenna exhibits planar profile which eliminates the need for cross and multi-layered construction thus resulting in ease of fabrication and reduced cost. The proposed antenna design is simulated using Finite Element Method based software. Reported simulations results demonstrate satisfactory performance when the antenna is mounted on various sizes of metal plate.

Keywords: Input impedance matching, metallic objects, patch antenna, radio frequency identification (RFID), Ultra-High Frequency (UHF)

INTRODUCTION

Due to pervasive and rapid adoption of Radio Frequency Identification (RFID) technology in supply chain management, logistics and healthcare sectors in recent years, many efforts have been put in improving the system as well as finding a new way to exploit the technology (Darianian and Michael, 2008; Dobkin, 2008). RFID can be classified as an automatic identification (Auto-ID) technology based on radio frequency (RF) to identify and locate an object without the need of human intervention unlike some conventional system such as optical barcode and fingerprint (Finkenzeller, 2003). Several advantages of RFID are it does not require Line Of Sight (LOS) to operate, capable of simultaneous multiple read and write, high transmission rate and large storage capacity. A basic RFID system is made of a reader and tag. Tag is attached to an object for the purpose of identifying and tracking the item, while reader serves to read the unique information carried by the tag in its memory when it is within the reader's vicinity. Tag in its basic form consists of an antenna and a microchip. On the other hand, reader is equipped with transceiver, transmitting and receiving antenna and processing unit to perform a much more complex operation than that of a tag. In most applications, host computer or a network is connected to the reader so as to perform post-processing activity such as constantly updating the movement of the tracked items in its database.

RFID can be categorized into several types according to their operating frequency, means of powering the tag and protocols employed to govern the communication (Guha and Antar, 2011). Low frequency (125-134 kHz) and high frequency (13.54 MHz) systems interacts by inductive coupling between reader and tag coils in the near field region. The read range of these systems is thus limited to about 1 meter. Meanwhile, ultra-high frequency (860-960 MHz) and microwave (2.4 GHz) systems communicate through the travelling electromagnetic wave between reader's and tag's antenna (Marrocco, 2008). As a result, both systems are able to realize a longer read range with higher transmission rate and better storage capability hence rapidly becoming preferred solutions. Nevertheless, Low Frequency (LF) and High Frequency (HF) are still finding its applications in area where secured communication is of utmost interest due to it closed contact operation. Tag can be divided into three main types which are active, semi-active and passive tag. This classification is based on how the tag is powered up. Active and semi-active tag are equipped with internal power source (i.e., battery) while passive tag is required to draw energy from the incoming electromagnetic wave emitted by the reader. In passive UHF RFID system, a reader sends a command to tag within its proximity by modulating RF signal in the 860-960 MHz frequency range. From the incoming RF signal, energy is drawn by the tag to operate the microchip. To send a response to the reader, a back-scattering modulation is used (Finkenzeller, 2003). Tag modulates the reflected signal by varying its input impedance between two states (matched and

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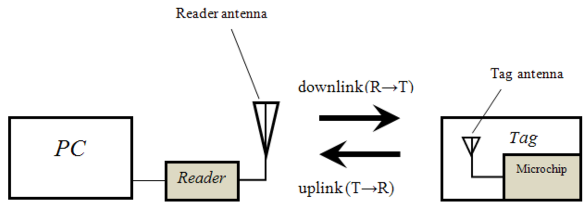


Fig. 1: General operating mechanism of RFID system

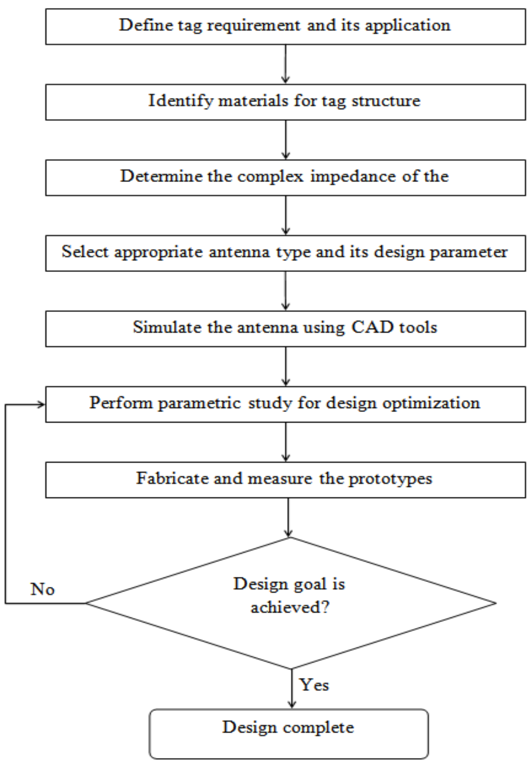


Fig. 2: Design process of RFID tag antenna

mismatched) according to its response. As a result, two distinct signal powers are received by the reader to demodulate the signal. Figure 1 illustrates a general RFID system operation. Currently, several standards are used to govern the RFID systems which are ISO, Class 0, Class 1 and Gen 2 (Rao *et al*., 2005) etc.

In passive UHF system, tag antenna is one of the important factors that determine the overall performance of the system. Due to the absence of internal power source, a good antenna design is crucial to ensure ample power is extracted from the RF signal to be delivered to the microchip. Several considerations are required when designing a tag antenna such as frequency range, size, cost, read range, compatibility with surrounding objects and polarization. Reviews on the UHF tag antenna design are well documented in (Rao *et al*., 2005; Marrocco, 2008) outlining various requirements and techniques used to build tag antenna. Figure 2 shows the design flow of the proposed antenna. In UHF RFID system, each country is allocated with its own frequency band. For North and South America, 902-928 MHz is used; Europe utilizes 865-868 MHz frequency band while 950-956 MHz band is adopted by Japan and some Asian countries (UHF Regulations, 2012). As such, most of the available tags are built according to a specific country thus limits its operation only in that particular country. To be able to work on the universal level, a wideband tag antenna is necessary where tagged objects can be moved from one country to the other without the need of multiple tags attached to it.

The most commonly used tag antennas are variation of label-typed modified printed dipole antenna. The utilization of this antenna is driven by its simple form, low cost, conformal to the attached objects and having an omnidirectional radiation pattern. Various works are found on literature on this type of antenna (Choi *et al*., 2006a; Jeon *et al*., 2006). Several works have been presented by Fang *et al*. (2008) and Monti *et al*. (2010) with the aims to miniaturize the size, increase the read range and improve the radiation characteristic of the antenna. However, it has been reported that these tag suffers performance degradation when attached to metallic objects (Ukkonen *et al*., 2005; Prothro *et al*., 2006; Ghannay *et al*., 2009). The cancellation of the incoming and reflected signal has caused a shift in operating frequency, degradation of impedance matching and distortion in radiation pattern which causes the reader not able to read the tag.

In order to mitigate this problem, several attempts have been made. One of the most commonly used solutions is to separate the tag from the metal surface by the use of foam spacer so that only constructive interference exist between the incoming and the reflected signal. However, due to the bulky structure, it is not suitable to use in most RFID applications. Another approach is to implement grounded antenna like Planar Inverted-F Antenna (PIFA) and micro strip (patch) antenna. Since both antennas operate on a ground plane, the metal surface would act as an extension of that ground plane hence giving little effects to the radiation characteristic of the antenna. Some works on PIFA are presented in (Hirvonen *et al*., 2004; Kwon and Lee, 2005; Choi *et al*., 2006b). The reported results show that the antenna is able to work when mounting on metallic objects. However, the antennas exhibit complex configuration due to cross-layered construction hence making it difficult to fabricate. Meanwhile, various types of micro strip antennas for metallic application have been proposed by Son *et al*. (2006), Mo *et al*. (2008), Xu *et al*. (2008), Lu and Hung (2010), Son and Jeong (2011) and Wu *et al*. (2011). Although the presented patch antennas are able to work on metal object, they either have narrow bandwidth or cross and multi-layered construction in their design. To ensure successful implementation of RFID system, tag must be as cheap as possible. Due to this, micro strip patch antenna with complex structure is costly and not suitable for mass production. Moreover, the antenna must also exhibit wide bandwidth to enable it to operate worldwide.

In this research, a low-profile planar patch antenna with wideband characteristic for metallic application is presented. By eliminating the cross and multi-layered structure in the design, the antenna can be easily fabricated therefore reducing the cost of the antenna. To realize a wideband operation, two gap-coupled C-shaped radiating patches are utilized to excite two resonant modes close to each other.

ANTENNA DESIGN

The most important criteria of tag performance is the read range. It is the maximum attainable distance at which the backscattered signal form the tag can be detected by the reader. Due to higher reader sensitivity compared to tag, the read range is often limited by tag response threshold, P_{th}. The Friss free-space formula (Rao *et al*., 2005) for the calculation of the read range, r, is expressed in Eq. (1):

$$r = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_t(\theta,\phi) G_r(\theta,\phi) p\tau}{P_{th}}} \quad (1)$$

where, λ is the free-space wavelength of the operating frequency, P_t represents the reader's transmitted power, G_t is the gain of the reader's transmitting antenna, G_r is the gain of the receiving tag antenna, p accounts for the polarization mismatch between the antenna and τ is the power transmission coefficient. The power transmission coefficient which measures the impedance mismatch between tag antenna and the microchip (Marrocco, 2008) can be expressed by Eq. (2):

$$\tau = \frac{4R_{chip}R_A}{|Z_{chip}+Z_A|} \leq 1 \quad (2)$$

where, $Z_A = R_A + jX_A$ is the complex impedance of the antenna and $Z_{chip} = R_{chip} + jX_{chip}$ represents the complex input impedance of that microchip. Another parameter often used to calculate the impedance mismatch between the antenna and microchip is return loss, *RL* (Bird, 2009). In general, return loss is a measure of the effectiveness of power delivery from a transmission line to a load where in this case the transmission line is represented by the tag antenna with microchip as its load. Return loss (dB) is defined by Eq. (3)

$$RL = 10\ \log_{10}\left(\frac{P_{in}}{P_{ref}}\right) \quad (3)$$

where, P_{in} and P_{ref} are the power incident on the load and power reflected back to the source. High value of return loss indicates a good matching between the line and the load. Furthermore, the reflection coefficient, Γ_{tag}, between the complex antenna impedance and microchip complex input impedance is given by Eq. (4):

$$\Gamma = \frac{Z_{chip} - Z_A^*}{Z_{chip} + Z_A} \quad (4)$$

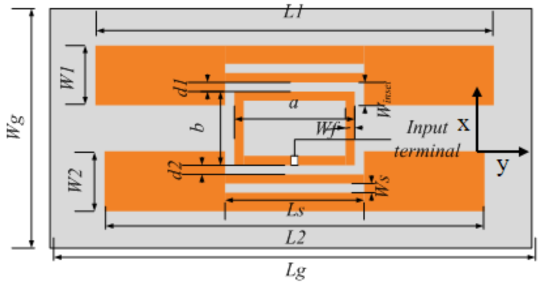
Return loss can be further related to the input reflection coefficient as shown in Eq. (5):

$$RL\ (dB) = -20\ \log_{10}|\Gamma| \quad (5)$$

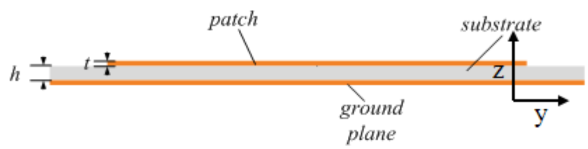
Based on Eq. (1), it can be seen that the performance of tag antenna can only be improved in terms of its power transfer coefficient and antenna gain as other parameter are fixed according to each country's regulations. Since a trade-off between gain, bandwidth and antenna volume is inevitable, careful design consideration is made to meet the design requirements of the antenna. For performance evaluation, half-power impedance bandwidth (RL ≥3 dB) which accounts for half of the radiated power absorbed by the tag antenna (Son *et al*., 2006; Huang *et al*., 2009; Lu and Hung, 2010; Son and Jeong, 2011) is adopted in this study.

Impedance matching is of great importance in RFID tag antenna design. A good impedance matching ensures sufficient power is delivered to the microchip thus enabling it to operate. It is known that microchip inherits capacitive reactance due to its energy-storage property. Therefore, tag antenna needs to presents inductive impedance at its input terminal to achieve conjugate impedance matching. There are varieties of available tag microchips whose input impedance vary from one another. In this study, tag chip manufactured from Alien Technology, Alien Higgs-3 for EPC Class 1 Gen 2 RFID is chosen as a reference microchip. The exhibit complex impedance of the tag chip is $Z_{chip} = (31 - \text{j}212)\Omega$ at 915 MHz. Several impedance matching techniques used to match the antenna and the microchips have been summarized by Marrocco (2008). In this design, inductively coupled feed loop technique (Son and Pyo, 2005) is employed to realize the impedance matching between the proposed antenna and the microchip. For the radiating element of the antenna, two C-shaped patches are used. Both of the patches are fed by the same feeding network thus simplifying the matching element. The lengths of both patches are slightly different from one another so that they resonate at two different frequencies adjacent to each other to form a wide impedance bandwidth to cover the entire range of UHF band. At both of the resonant frequencies, the resistance and the reactance (Son and Pyo, 2005) of the tag antenna are given by Eq. (6) and (7):

$$R_{A,0} = R_A(f_0) = \frac{(2\pi f_0 M)^2}{R_{rb,0}} \quad (6)$$



(a)



(b)

Fig. 3: The geometry of the antenna, (a) top view and (b) side view

$$X_{A,0} = X_A(f_0) = 2\pi f_0 L_{loop} \quad (7)$$

where, f_0 the resonant frequency of the patch, M is the mutual inductance between the patch and the loop, R_{rb} represents the resistance of the patch and L_{loop} is the self-inductance of the feed loop. Based on the Eq. (6) and (7), it is evident that $R_{A,0}$ and $X_{A,0}$ can be adjusted independently to match the microchip impedance.

Figure 3 illustrates the geometry of the proposed antenna. The C-shaped patch can be derived from a rectangular micro strip antenna where a slot is cut along one of its non-radiating edge (Kumar and Ray, 2003) .To initially calculate the resonant frequency of rectangular patch without the cut slot (Balanis, 2005), Eq. (8) shows the relation:

$$f_0 = \frac{c}{2\sqrt{\varepsilon_e}}\left[\left(\frac{m}{L}\right)^2 + \left(\frac{n}{W}\right)^2\right]^{1/2} \quad (8)$$

where, L and W are the length and width of the patch respectively and m and n are the modes along L and W. ε_e denotes the effective dielectric constant as shown in Eq. (9):

$$\varepsilon_e = \frac{(\varepsilon_r+1)}{2} + \frac{(\varepsilon_r-1)}{2}\left[1 + \frac{10h}{W}\right]^{-1/2} \quad (9)$$

It is observed that the calculated resonant frequency of the rectangular patch to be reduced once a rectangular slot at one side of its non- radiating edge is cut to form C-shaped patch. This is due to increase of electrical path of the antenna. Therefore, the physical length of the antenna can be reduced to achieve smaller form factor compared to typical rectangular patch design. The inexpensive FR-4 epoxy glass with relative dielectric constant, ε_r = 4.4 and tangential loss, $tan\delta$ = 0.002 is chosen as a substrate. The high tangential loss of the substrate reduces the Q-value of the antenna hence enhances the bandwidth. The thickness of the substrate, h = 1.6 mm is selected mm to keep it low-profile. The size of the substrate and the ground are both 87 mm×45 mm. As for the patch and the ground plane, copper with thickness, t = 0.0358 mm is used. The proposed antenna design is simulated using Ansoft HFSS v13 and the simulated results and detailed analysis are presented in the next section.

RESULTS AND DISCUSSION

To realize a wideband characteristic, good impedance matching between the proposed antenna and the microchip for the whole frequency range of UHF band is required. To achieve this, two C-shaped patches that have resonant modes close to each other is adopted. To feed both of the patches, inductive coupled loop feed is sandwiched between them. This allows only a single feeding network to be used to feed both of the radiating body. Based on Eq. (7), the input reactance of the antenna can be tuned to conjugate match that of the capacitive impedance of the microchip by varying the dimensions of the loop, a and b. On the other hand, the distance of both patches to the feed loop, $d1$ and $d2$ can be adjusted accordingly to present a good match with the microchip's resistance value. In addition, a thin slot is cut at the center of both patches to increase the coupling strength between the loop and the patch where significant increase in resistance is accomplished at the antenna input terminal. The advantage of using this matching technique is that independent adjustment can be made to achieve the desired resistance and inductance value. Parametric refinement has been performed using the simulator to find the optimized values to obtain good impedance matching over the entire range of UHF RFID band. Since the aim of this study is to design wideband tag antenna that is able to be used for metal applications, two scenarios where the antenna are mounted on two different sizes of metal plate were simulated to observe its effects on the antenna performance. The sizes of the metal plate are taken to be 200×200 and 400×400 mm^2 respectively. The optimized antenna parameters are summarized in Table 1.

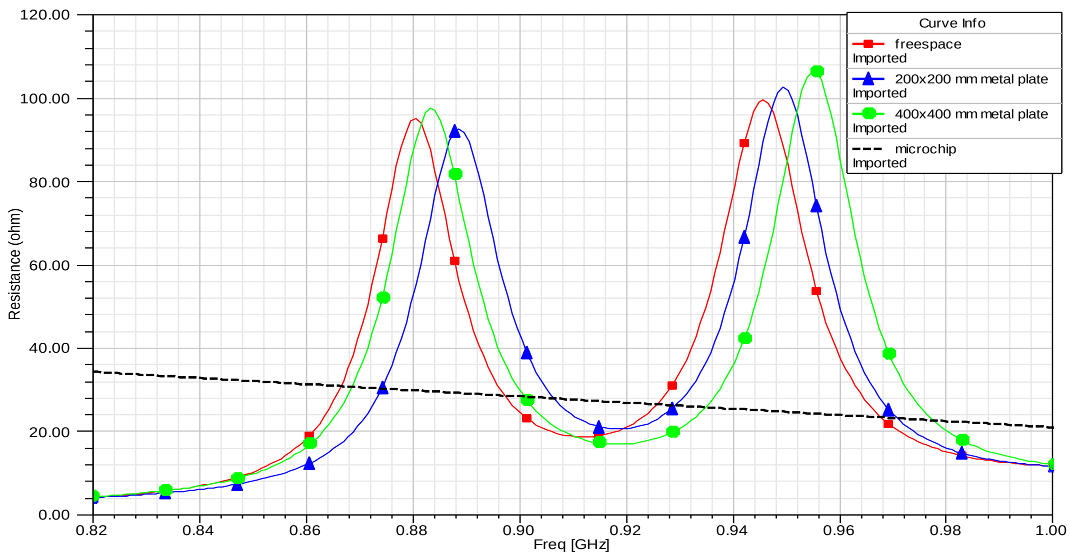
Figure 4 depicts the simulated complex impedance of the antenna together with the corresponding conjugate impedance value of the microchip. As predicted, due to the excitation of two resonant modes of the radiating patches, good match for resistance and reactance between the proposed antenna and the microchip is obtained throughout the frequency ranges thus producing wide impedance bandwidth. Only slight frequency shift is observed when the antenna is

Table 1: Optimized design parameters of the antenna

Parameter	Value (mm)
$W1$	10
$L1$	74
$W2$	10
$L2$	69
W_s	1
L_s	30
$d1$	2
$d2$	2
W_{inset}	4
t	0.0358
h	1.6
W_f	2
a	29
b	10
Ground plane and substrate	87×45

mounted on metal plate. This is probably due to the reduced of the fringing field when being attached on metal plate as compared to without metal plane condition.

In order to reduce the physical size of the antenna, rectangular slot was cut at one side of the non-radiating edge of each patch. The existence of the slot causes the meandering of electrical path length making it longer than that of the rectangular patch without slot. As a result, resonant frequency of the patch is reduced hence allowing for miniaturization of the antenna. The surface current distributions of the antenna at both of the resonant modes are shown in Fig. 5. The meandering of the electric current is due to C-shaped patch as



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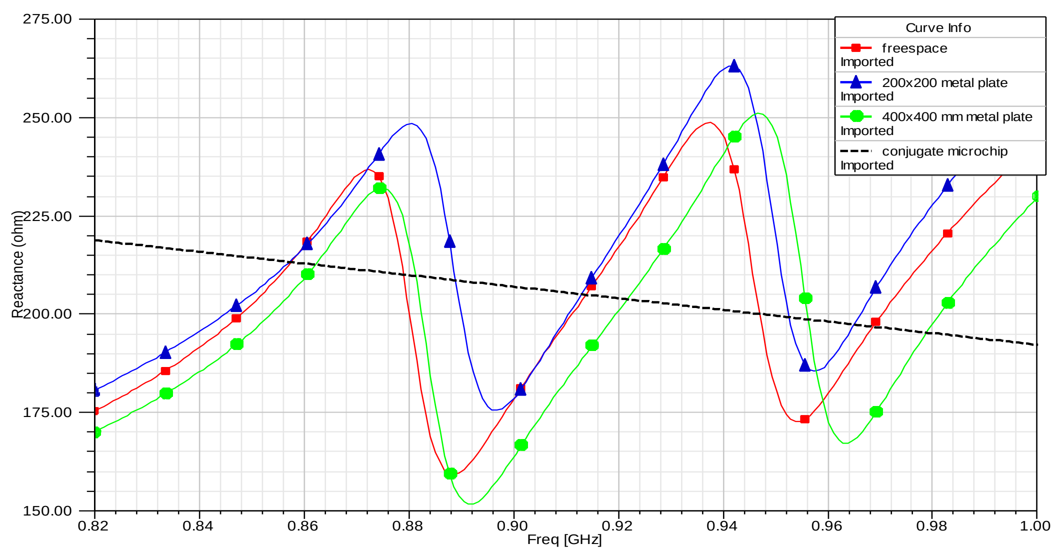
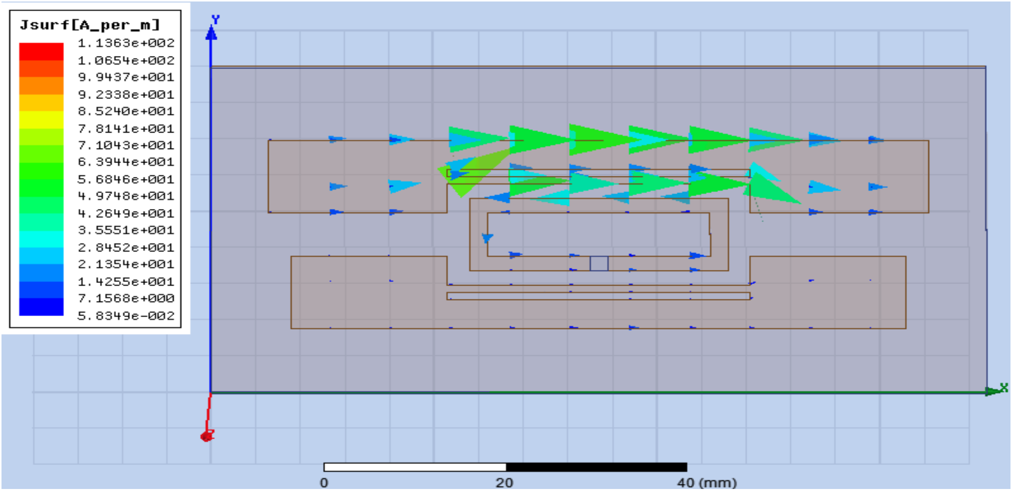


(b)

Fig. 4: Simulated impedance of the antenna and the microchip conjugate impedance value against frequency, (a) resistance and (b) reactance value against frequency



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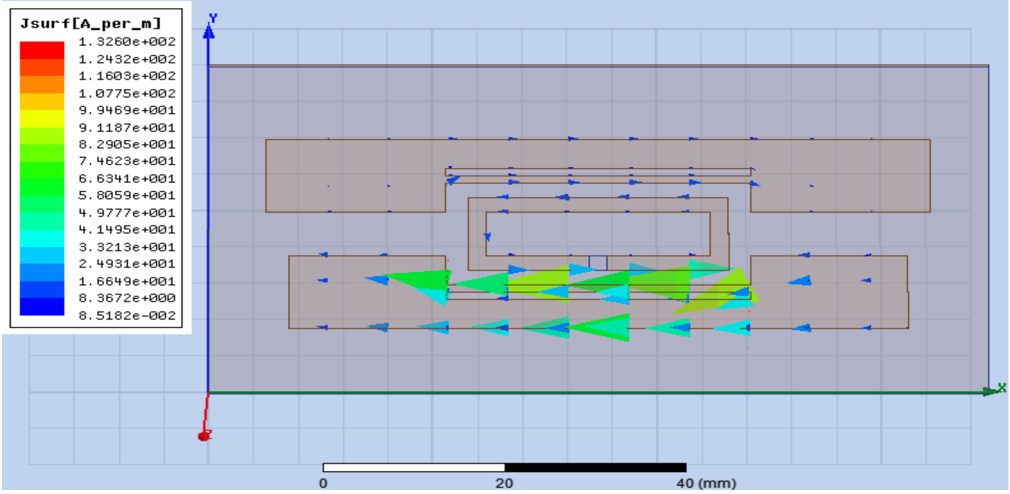
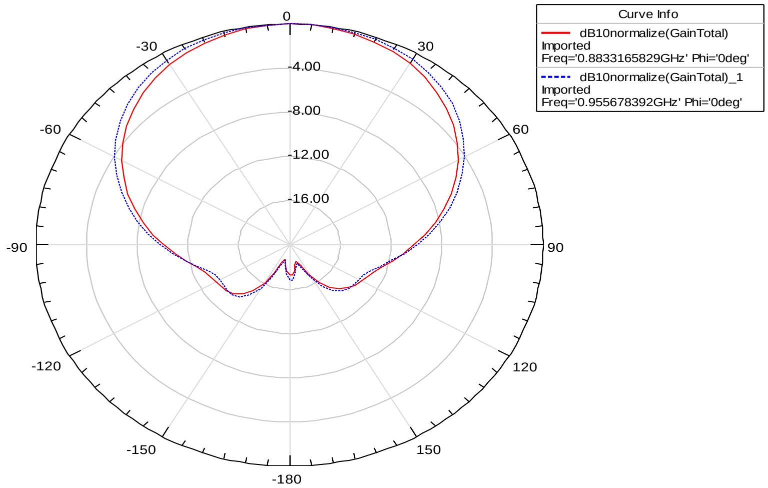


(b)

Fig. 5: Surface current distribution of the antenna at two resonant modes, (a) 883 MHz and (b) 953 MHz



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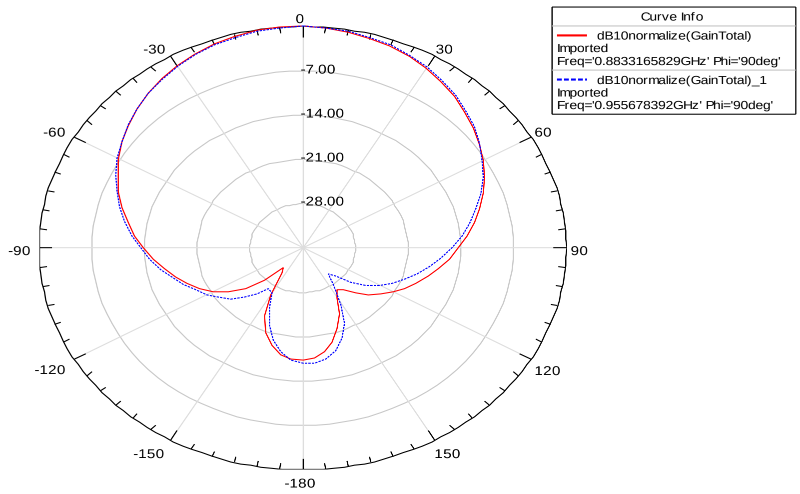

(b)

Fig. 6: (a) Normalized E-field and (b) normalized H-field radiation pattern at two resonant frequencies

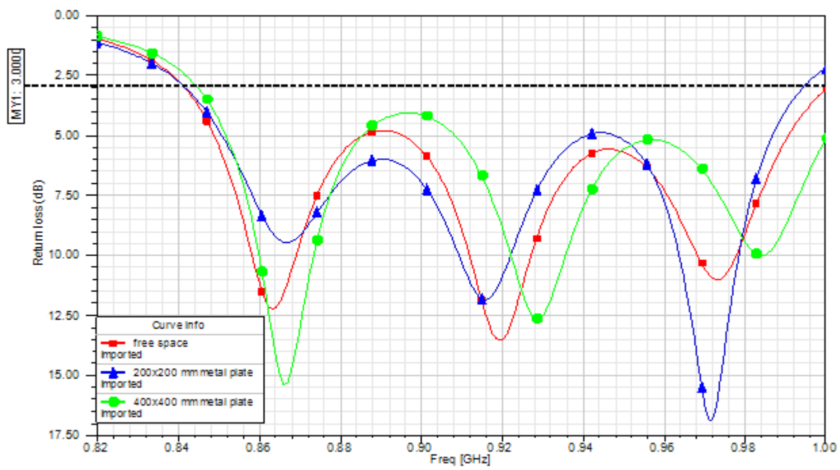

Fig. 7: Return loss (dB) of the proposed antenna

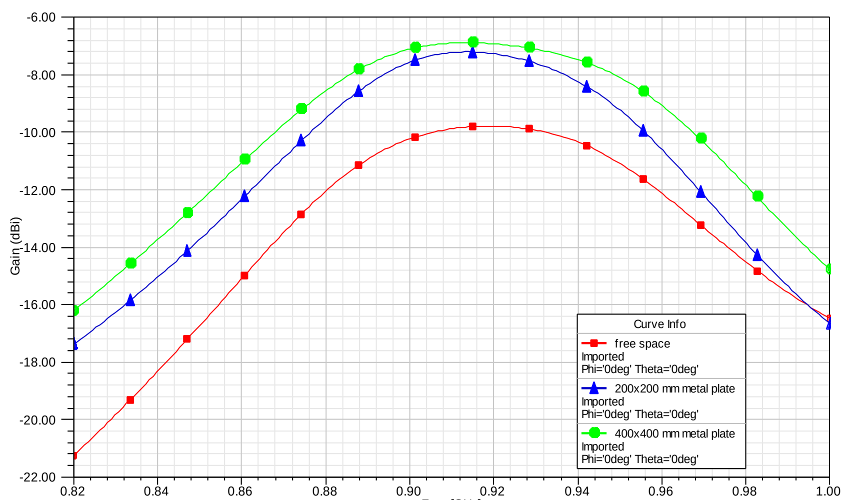

Fig. 8: Peak antenna gain of the proposed antenna

Table 2: Theoretically calculated read range of the proposed antenna

Country/Region	Center frequency, f_c (MHz)	EIRP (W)	Read range (m) Without metallic plane	200×200 mm	400×400 mm
Europe	886	3.3	2.36	3.15	3.85
North America	915	4	4.08	5.51	5.37
Japan	954	4	2.91	3.5	3.97

explained above. The radiation patterns at the E-plane and H-plane are shown in Fig. 6.

The simulated half-power impedance bandwidth (RL ≥3 dB) of the antenna is illustrated in Fig. 7. It is seen that the impedance bandwidth of all three cases are able to cover the entire UHF RFID band for worldwide operation. The discrepancies of the bandwidth obtained are mainly due to the slight shift of the resonant frequencies of the antenna due to the effect of the metal plate. To give better assessment of the antenna performance, the simulated total gain is given in Fig. 8. The low gain of the antenna is mainly due to the loss and thin substrate structure as well as its small form factor. However, improvement on the antenna gain is seen when it was mounted on the metal plate. Theoretically calculated read ranges of the proposed antenna for several major countries are given in Table 2. It is seen that maximum read range of over 3 m is achieved throughout the entire UHF band when the antenna is mounted on metallic objects.

CONCLUSION

In this study, a new RFID tag antenna for metallic application is proposed. To realize wideband impedance bandwidth for universal UHF band application, two gap-coupled C-shaped patch having resonant modes close to each is employed. An inductive coupled loop feed is used as a matching scheme to perform the conjugate match to the microchip. The complete low profile structure of the proposed antenna eliminates any cross and multi-layered construction which would significantly reduce the complexity of the antenna fabrication and subsequently lead to potential cost saving. The simulated half-power impedance bandwidths for all three cases exceed the required impedance bandwidth of 11.16% for worldwide operation. Moreover, theoretically calculated read range of over 3 m is obtained when the proposed antenna is attached to metallic surface over the entire UHF RFID band.

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