Design and Testing of A Small Passive UHF RFID Tag for Metallic Item Identification

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Abstract[*]

Passive UHF Radio Frequency Identification (RFID) tags are potentially low cost and offer good read range for object identification in various types of applications. However, the performance of conventional passive UHF RFID tags will be greatly affected when the tags are attached to metallic objects. In this paper, a small passive UHF RFID tag consisting a loop antenna designed specifically for attaching to metallic objects is presented. Theoretical design steps for this tag design, as well as significant simulation results are included. The results for practical read range performance measurement of this tag are also presented.

1. Introduction

Radio Frequency Identification (RFID) is a technology used for object identification via radio waves. A basic RFID system consist of tags, one or more readers, and a network system for data handling [1]. The first idea of RFID has been traced back to as early as the 1940's [2]. However, it is only recently that RFID is receiving increasing attention, especially in terms of research and development, due to the widening of the applications of this technology in various areas. Examples of RFID applications can be found in [2][3]. Today, some of the common operating frequencies for RFID are 125 kHz (LF), 13.56 MHz (HF) and 860 - 960 MHz (UHF).

Passive UHF RFID tags are able to provide good read ranges for object identification compared to LF or HF RFID tags, and they are also seen as potentially low cost. However, conventional planar passive UHF RFID tags will suffer a degradation in performance when attached to metallic objects or structures. The reason to this may be either due to the detuning of the resonant frequency of the RFID tag antenna or insufficient interrogation field from the RFID reader reaching and powering-up the tags.

The presence of metallic objects or structures is certainly unavoidable. Hence, for widespread deployment, passive UHF RFID tags that are suitable for tagging metallic objects are needed. In this paper, we present a small passive UHF RFID tag with a simple rectangular loop antenna design that is suitable for attaching to metallic objects. The design methodology for this tag design is also presented. The design has been evaluated through simulations and simple empirical measurements. Significant calculation, simulation and performance measurement results are presented in this paper.

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[*] This paper is based on "A Small Passive UHF RFID Tag for Metallic Item Identification" by M. L. Ng, K. S. Leong, and P. H. Cole, in 21st International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC 2006), Chiang Mai, Thailand, 2006.

2. Design Concept

When designing an RFID tag suitable for attaching to metallic objects, the first point to be considered is the behaviour of the interrogation fields (from the RFID reader) near a metallic surface. According to the theory of boundary conditions for magnetic field, there are only tangential components and no normal components of this field at the metallic surface [4]. Fig. 1 shows a simplified illustration of magnetic fields near a metallic surface. Also, the magnetic field (tangential component) from a normally directed travelling wave will be doubled when it is very near the metallic surface.
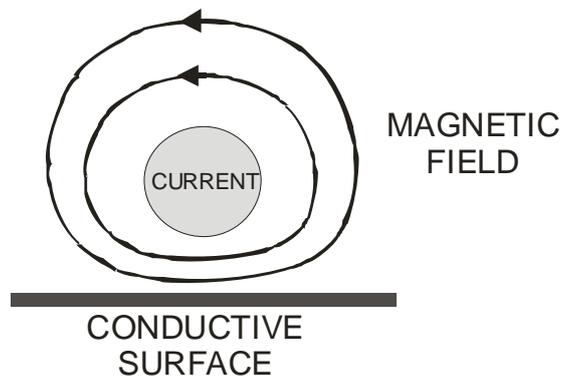
Figure 1: Magnetic fields near a metallic surface

The RFID tag design presented here exploits the fact above by having a loop antenna oriented such that the plane of the loop is perpendicular to the plane of the metallic surface to which the RFID tag will be attached. With this orientation, the idea is to have the rich concentration of magnetic field near the metallic surface to couple to the loop antenna of the RFID tag.

Many different types of loop antenna can be considered for the tag antenna. The circular loop antenna is the most common among all loop antennas, however this antenna will occupy too much height if it has adequate area and is oriented in a way that the plane of the loop is perpendicular to the plane of the metallic surface. Hence, a rectangular loop antenna is chosen. Fig. 2 shows the structure of the RFID tag design that consists of a rectangular loop antenna and a RFID tag chip. As can be observed, the rectangular loop antenna is not a regular planar loop antenna constructed with circular wire. Instead, it is made of a wide copper strip of width W_{rec}. The reason for this is that, by having a certain width, the antenna will provide a better coupling volume [5].
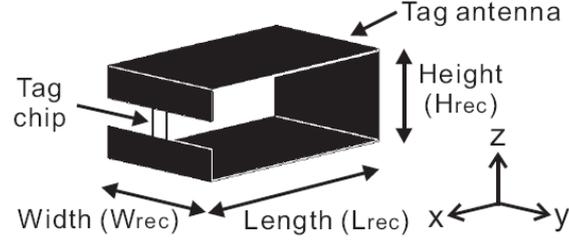
Figure 2: Structure of the RFID tag with a rectangular loop antenna.

3. Approach

3.1. Theoretical Calculations

The calculations for this loop antenna are the same as the calculations for regular loop antennas made of circular wire, except that the dimension for the cross section of the wide copper strip of this antenna has to be converted to its equivalent circular wire radius r before calculations are performed. Deriving from the equivalent radius expression given in [6], the equivalent radius r corresponding to the wide copper strip of width W_{rec} is:

$$r \approx 0.2 W_{rec} \tag{1}$$

The rectangular loop antenna with the structure presented here can be approximately represented by a resistor with radiation resistance R_{rad} and an inductor with inductance L_{ant} in series (assuming it to be lossless, electrically small and of negligible self-capacitance). Small loop antennas with the same loop area carrying a uniform current have the same radiation resistance. The radiation resistance and inductance of the rectangular loop antenna are determined using the expressions found in [6] that correspond to a small circular loop antenna with loop radius R and circular wire radius r. The expressions are [6]:

$$R_{rad} = 20\pi^2 (\beta R)^4 \tag{2}$$

$$L_{ant} = \mu_0 R \left[\ln\left(\frac{8R}{r}\right) - 2 \right] \tag{3}$$

where $\beta = (2\pi)/\lambda$ is the free space propagation constant with wavelength λ, and $\mu_0 = 4\pi \times 10^7$ Hm^{-1} is the free space permeability.

The RFID tag chip used in this design can be represented by a resistor with resistance R_{chip} and a capacitor with capacitance C_{chip} in parallel. For a start, the values of $R_{chip} = 3$ kΩ and $C_{chip} = 1.15$ pF are used in the design. The RFID tag is designed to operate in the UHF band

at around the frequency of 915 MHz. For this frequency, the equivalent impedance of the chip Z_{chip} is 7 - j150 Ω.

We know that the maximum power transfer will occur when the tag antenna impedance is equal to the conjugate of the tag chip impedance. To achieve this, the usual method of including an impedance matching network to the design is not used. Instead, the physical dimension of the rectangular loop antenna is adjusted to provide sufficient inductance to be tuned with by the capacitance of the tag chip. The trade-off of this method is that the small rectangular loop antenna will be able to provide sufficient inductance but not the resistance that corresponds to the tag chip impedance, since it is a characteristic of small loop antennas to have low radiation resistance. However, this method is still used due to the aim of maintaining the simplicity and low cost of the design.

The height H_{rec} and length L_{rec} of the rectangular loop antenna are fixed to 10 mm and 25 mm respectively in order to have a rectangular loop with perimeter of approximately $\lambda/5$. A circular loop that has an equal area to this rectangular loop will have a loop radius R = 9 mm. Since H_{rec} and L_{rec} are fixed, the only variable is the width W_{rec} of the rectangular loop antenna. Using (1) and (3) with R = 9 mm, to obtain a loop antenna inductive reactance of 150 Ω at 915 MHz (L_{ant} = 26 nH), it is calculated that W_{rec} of 5 mm is required. In addition, using (2), the antenna is expected to have $R_{rad} \approx 0.17 \Omega$ in free space.

3.2. Simulations

Using the rectangular loop antenna dimensions calculated theoretically (H_{rec} = 10 mm, L_{rec} = 25 mm and W_{rec} = 5 mm), the RFID tag design is modelled and simulated using Ansoft HFSS. Two different cases are considered: (1) RFID tag in free space; and (2) RFID tag positioned near a metallic surface. The latter case aims to predict the effect of the metallic surface towards the characteristics of the RFID tag antenna.

For the first case with the RFID tag in free space, the simulation result shows that the rectangular loop antenna has impedance Z_{ant} = 0.25 + j150 Ω at the frequency 915 MHz, which is quite close to the theoretically calculated values. The directivity pattern of this antenna in the yz-plane is as shown in Fig. 3(a). Since this antenna is a loop antenna, the directivity pattern of this antenna is very similar to that of conventional small circular wire loop antennas in free space, which is as expected. The peak directivity obtained from the simulation is 1.3 dB.

In the second simulation case, the RFID tag is positioned near a metallic plane of size 1.5λ $\times 1.5\lambda$ with the plane of the rectangular loop antenna perpendicular to the metallic plane. The antenna and the metallic plane is separated by a small gap of 3 mm to prevent the antenna from making a direct short-circuit to the metallic plane. In addition, in practical or real-life implementation of this RFID tag design, adhesives will be inserted within this gap to allow the tag to be attached on metallic items.

The simulation result for the second case shows that the rectangular loop antenna has impedance Z_{ant} = 0.54 + j151 Ω at the frequency 915 MHz. Comparing with the first case (tag

in free space), it is observed that the reactance of the antenna has not changed much when the RFID tag is near a metallic surface. Only the resistance has changed, with the second case having almost twice the resistance in the first case. The directivity pattern of the antenna in the yz-plane corresponding to the second case is as shown in Fig. 3(b). It can be seen in Fig. 3(b) that the antenna pattern has been significantly changed with the presence of a metallic plane near it. The peak directivity obtained from the simulation is 6.4 dB. Also shown, in Fig. 4, are the 3-dimensional polar plot of the simulated directivity pattern for the first and second cases.

(a) (b)
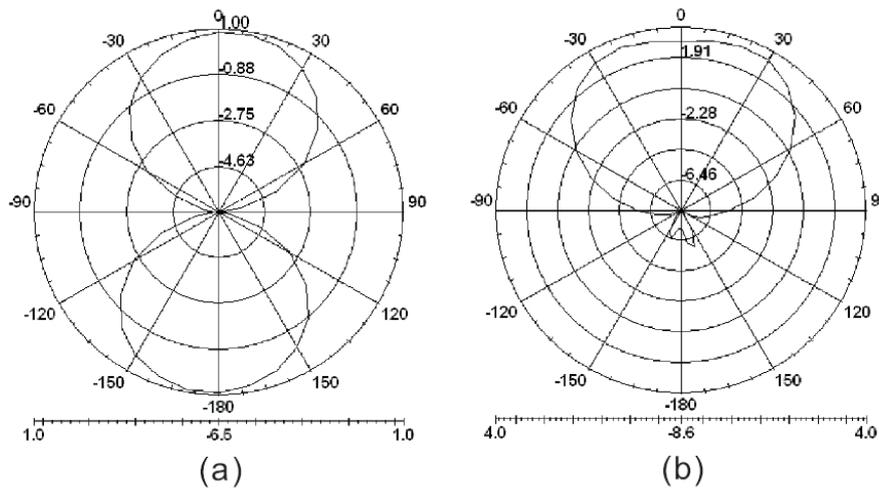
Figure 3: The yz-plane radiation pattern of the RFID tag antenna: (a) tag in free space; (b) tag located 3 mm above a 1.5×1.5λ metallic plane (Antenna dimension: H_{rec} = 10 mm, L_{rec} = 25 mm and W_{rec} = 5 mm).

(a) (b)
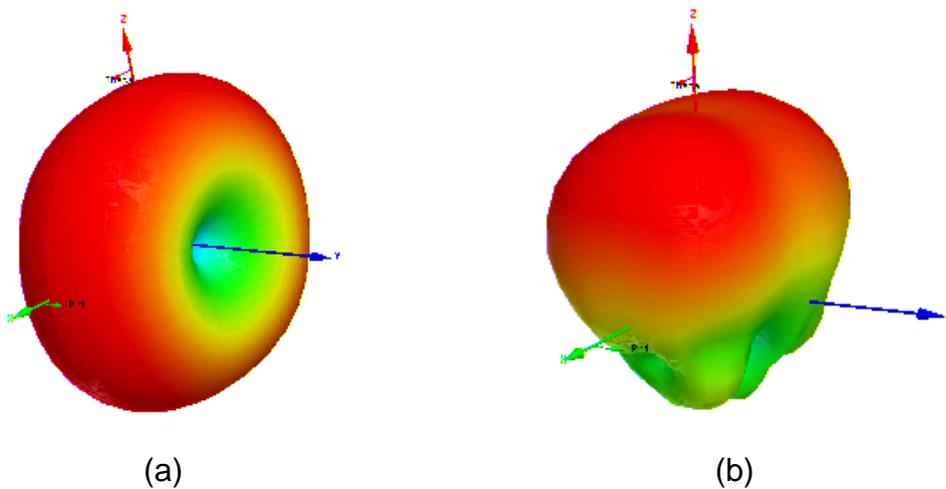
Figure 4: The directivity pattern of the RFID tag antenna in the 3-dimensional polar plot form: (a) tag in free space; (b) tag located 3 mm above a 1.5×1.5λ metallic plane (Antenna dimension: H_{rec} = 10 mm, L_{rec} = 25 mm and W_{rec} = 5 mm).

The simulation results above shown that, for this RFID tag design, the presence of a metallic plane does not affect the reactive impedance of the antenna. Hence, this tag will most likely not suffer from detuning of the resonant frequency when it is attached near a metallic surface. In addition, the presence of a metallic plane has also enhanced the directivity of the antenna.

4. Design Implementation and Fine-tuning

The tag design is implemented according to the illustration in Fig. 2. For the making of the loop antenna, a copper tape has been used and is cut according to the calculated dimensions. For better durability of the tag, the copper tape is wrapped around a small rectangular block of ABS plastic to maintain the shape of the tag antenna. Besides being low cost and light weight, ABS plastic is chosen because it is found that it will not put significant effect on the performance of the tag.

For the investigation of the resonant frequency, a network analyser is set to couple by means of a small un-tuned loop to the tag, and to measure the reflection from that loop over a set frequency range. The small un-tuned loop used is 7 mm in diameter and is made from the centre conductor at one end of a short length of the coaxial cable (Fig. 5). The output from the network analyser was 5 dBm.

By observing the reflection pattern on the network analyser, the approximate resonant frequency of the tag is found to be 650 MHz, which is much lower than expected. This may be caused by the variation of the actual tag chip capacitance in practice from the chip capacitance assumed during theoretical calculations, or by the additional self-capacitance of the loop. An impedance curve of the antenna over a frequency range obtained from simulation is used to estimate the self-capacitance of the antenna. The self-capacitance value is found to be quite large ($\approx$2.5 pF).

Figure 5: Small un-tuned loop

To estimate the actual total capacitance (consists of tag chip capacitance and antenna self-capacitance) that has tuned with the inductance of the rectangular loop antenna, the following expression is used:

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}} \quad (4)$$

where $f_{resonant}$ is the resonant frequency, and L and C are the inductance and capacitance of an inductor and capacitor in the circuit respectively. We know from earlier calculations that the rectangular loop antenna with dimension H_{rec} = 10 mm, L_{rec} = 25 mm and W_{rec} = 5 mm has an inductance L_{ant} = 26 nH. With the approximate measured $f_{resonant}$ = 650 MHz and using (4), the total resonating capacitance is estimated to be 2.3 pF.

Using the newly estimated capacitance value and using (4) again, in order for the antenna to resonate at around 915 MHz, it is calculated that a L_{ant} of 13 nH is required. Hence, to obtain this antenna inductance, using similar calculations method presented in Section 3, the rectangular loop antenna of the tag will need to have W_{rec} = 15 mm with H_{rec} and L_{rec} remaining the same.

The tag design with the new dimensions is simulated using HFSS for the cases where the tag is in free space and when the tag is near a metallic plane. The simulated results for both cases are as shown in Table 1. Comparing both cases, once again it is observed that the reactance has remained unchanged and the resistance has doubled for the latter case. The directivity pattern of the antenna in the yz-plane corresponding to the latter case is shown in Fig. 6. Also shown in Fig. 6, is the 3-dimensional polar plot of the simulated directivity pattern for the latter case.

Table 1: Simulation results for the RFID tag with rectangular loop antenna dimension H_{rec} = 10 mm, L_{rec} = 25 mm and W_{rec} = 15 mm

Tag Location	Antenna Impedance	Peak Directivity
Free Space	0.26+j91Ω	1.5 dB
Above Metal	0.53+j91Ω	6.5 dB

The tag design with the new dimensions is implemented and measured using the small un-tuned loop mentioned above. A resonant frequency of 870 MHz is measured, which is much closer to the expected value compared to the earlier case.
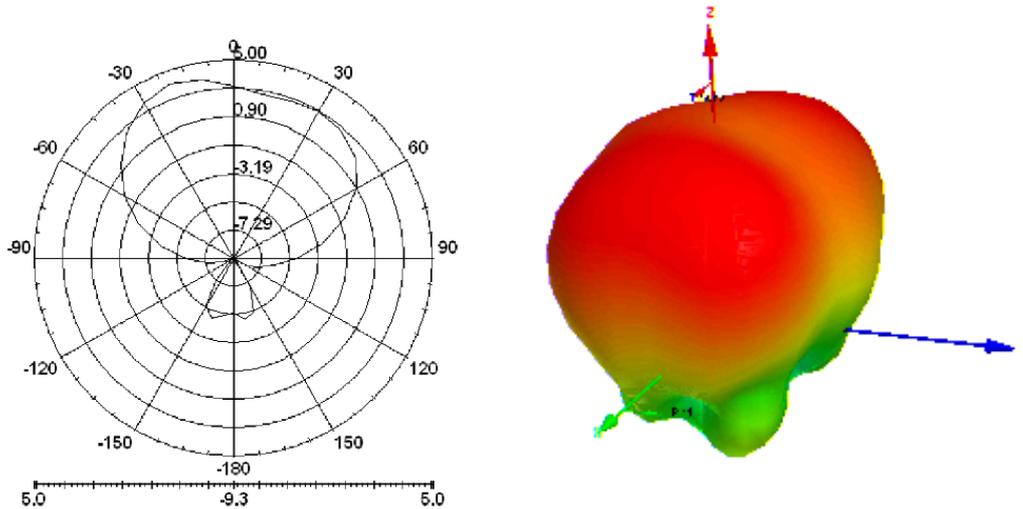
Figure 6: The *yz*-plane radiation pattern of the RFID tag antenna located 3 mm above a 1.5×1.5λ metallic plane (Antenna dimension: H_{rec} = 10 mm, L_{rec} = 25 mm and W_{rec} = 15 mm). Also shown is the directivity pattern in the form of a 3-dimensional polar plot.

5. Read Range Measurements

A RFID reader which has the ability to operate over the band 900 MHz to 940 MHz is set up to measure the read range performance of the RFID tag. The reader has an output peak power of approximately 250 mW. Taking into consideration of the 8 dBi gain circularly polarised reader antenna used, the total equivalent transmit power is approximately 1.6 W EIRP (Effective Isotropic Radiated Power). The RFID tag is placed 3 mm above a 1.5λ ×1.5λ, aluminium metallic plane. With the reader antenna radiating at normal incidence to the metallic plane, the read range measured at a number of frequencies within 900 MHz to 940 MHz is shown in Fig. 7.

At 915 MHz, a read range of approximately 0.83 m is achieved for the above specified total transmit power of the RFID reader. For a total transmit power of 4 W EIRP (e.g. in United States), the read range is expected to increase by approximately 1.6 times. A second RFID tag with the same dimension was made and the measured read range is consistent with that of the first RFID tag. Overall, the read range performance of this RFID tag is promising, with a good read range achieved over a wide frequency range. The reason to this is that the RFID tag antenna has enhanced performance when it is near a metallic surface, and the structure of this antenna has allowed good coupling to the magnetic components of the interrogation fields from the RFID reader near the metallic surface.
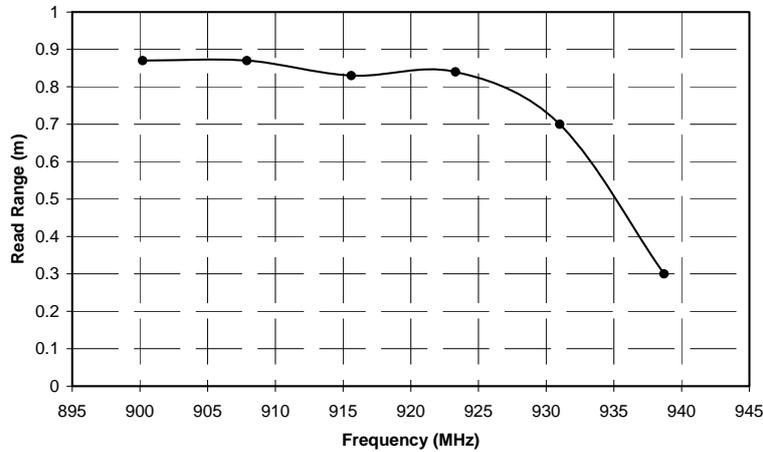
Figure 7: Read range measured over a frequency range for tag above an aluminium metallic plane.

6. Further Measurements

Further practical read range measurements have been performed on the tag by replacing the initial aluminium metallic plane with other metallic planes of the same size (1.5λ ×1.5λ) but of different materials. Two materials, stainless steel and copper, have been chosen. The read range results at a number of frequencies within 900 MHz and 940 MHz are shown in Fig. 8.

From the measurement results, it can be observed that the read range performances of the tag above a stainless steel metallic plane and a copper metallic plane are very close to that of the aluminium metallic plane case. This is a fortunate result as many of the intended applications of the loop are when attached to stainless steel objects.

7. Conclusion

This paper has presented a small passive UHF RFID tag with a simple rectangular loop antenna design that is suitable for tagging metallic objects. This design has been fine-tuned, implemented and tested, and has been shown to perform well when attached to a metallic structure. Future work on this RFID tag design will include further optimisation of the overall dimensions of the tag antenna. The work presented in this paper will be a useful contribution towards the RFID industry in terms of wide spread deployment of RFID involving the tagging of metallic objects.
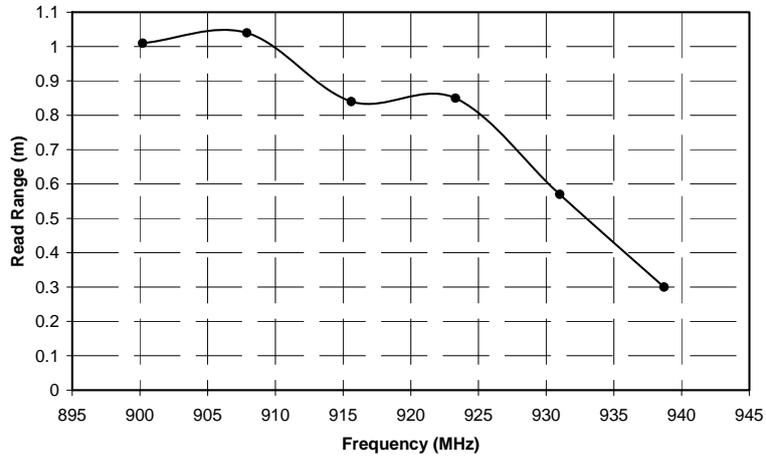
(a)
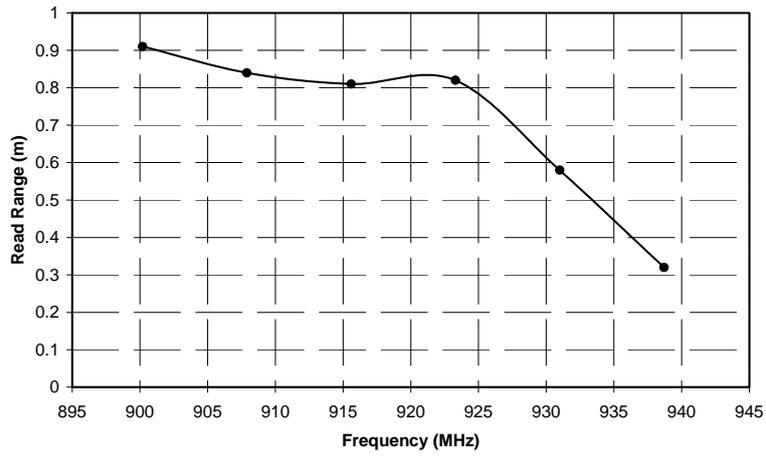
(b)

Figure 8: Read range measured over a frequency range for the tag above a: (a) stainless steel metallic plane; and (b) copper metallic plane.
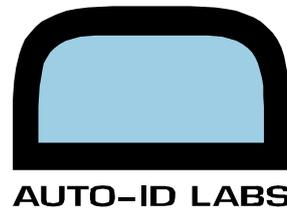
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