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RFID Tag Antenna for Metallic or Non-Metallic Surfaces

Bo Tao[1], Hu Sun[1, 2], and Omar M. Ramahi[2, *]

Abstract—A capacitively fed rectangular patch antenna for anti-metal RFID tag was studied. It was found that by using capacitively feeding and a thin micro-strip line, the input impedance could be stabilized with respect to ground plane size. As a result, the reading range degradation was avoided, and the presented antennas have almost the same reading range when used on metal or non-metal objects. The mechanism was explained by a basic antenna design and a transmission line model. Then a more practical compact design having much smaller size was presented. Prototypes of both the basic design and the compact design were fabricated and tested. The testing results validated the effectiveness of the designing method.

1. INTRODUCTION

Ultra high frequency(UHF) RFID technology has gained much research interest in logistic or retail management because of its high identification speed, long reading range and low cost [1]. The frequency of UHF RFID system ranges from 865 MHz to 915 MHz depending on regional regulations. However, most UHF RFID systems work in two frequency bands, 865 MHz and 915 MHz. Most widely used RFID tags are disposable label type inlays with meander-line dipole antennas [2], which could be made wide band and applicable to all kinds of dielectric objects without losing too much reading range. In some critical applications such as vehicle management or managements of metallic assets in general, durable and anti-metal tags with patch or micro-strip antennas are needed to maintain effective identification distance. An anti-metal tag means it is specially designed to work on metallic surfaces.

Classical patch antennas have inherent disadvantages, in particular narrow bandwidth which could be solved by various designs [3–11]. Nevertheless, another critical drawback, which is important especially for RFID applications, is the size of the ground plane or the size of the metallic surface. The antenna ground plane size affects the antenna performance due to the radiation admittance change caused by the diffraction effect from the edges of the ground plane [12]. In a RFID tag antenna, the ground plane is made only slightly larger than the patch to reduce size and cost. As a result, when the tag is tested in free space or on a large metallic surface, the performance could be totally different. This effect leads to significant variation in reading range when the tags are tested with or without metal.

This problem can be avoided by using larger ground plane, or compensated according to the specific design criterion. Novel designs like PIFA array antennas [13, 14] are capable of solving this problem, probably because the radiation edges are away from the antenna ground plane. Capacitive feeding was mainly used to improve the bandwidth of RFID tag antennas [3, 7, 10, 11]. In Ref. [10] capacitive feeding has been used to improve the bandwidth of a meandered patch antenna, and was also found that it made the reading range stable. However, its potential for reducing the reading range degradation was not investigated.

In this paper, we used a thin micro-strip line and capacitive coupling to feed rectangular patch. By using a qualitative transmission line model, it was found that this feeding method is capable of

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* Corresponding author: Omar M. Ramahi (oramahi@uwaterloo.ca).
[1] School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China. [2] School of Electrical and Computer Engineering, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada.

stabilizing the input impedance of the patch antenna, thus reducing the reading range degradation brought by different backing objects. Firstly, a basic design and its transmission line model were proposed and studied to explain the mechanism. A practical compact design having smaller size based on the same idea was presented. Prototypes of both the basic design and compact design were fabricated and tested giving reading ranges consistent with design predictions.

2. BASIC ANTENNA DESIGN

A basic design is shown in Figure 1. It is optimized to work around 865 MHz. The RFID chip is Alien H3 with input impedance of $24 - j190\,\Omega$. The primary dimensions are given by $W = 20$ mm, $L = 76.5$ mm, $g = 6$ mm, $W_s = 1$ mm and $L_s = 56$ mm. The antenna is patterned on a 30 mm × 170 mm FR-4 substrate backed by a ground plane. The antenna comprises a radiation patch, a coupling line to capacitively feed the radiation patch, a thin micro-strip line to match the antenna impedance to an RFID chip, and a pair of pads for soldering the RFID chip with one end connected to the ground plane by a *via*. The length of the coupling line is chosen to be the same as the width W of the radiation patch. The width of the coupling line is 2 mm.

3. QUALITATIVE TRANSMISSION LINE MODEL

The diffraction effect of the finite ground plane will affect the radiation admittance of the radiation patch [12] and lead to mismatch between the antenna input impedance and the RFID chip. The size of ground plane also affects the radiation pattern [15]. However, the impedance mismatch due to the change of radiation admittance has the dominate contribution to the reading range degradation of the RFID tag.

The transmission line model of the basic design is as shown in Figure 2, where Z_a is the input impedance measured at the coupling edge. A capacitor C_m represents the capacitive coupling between

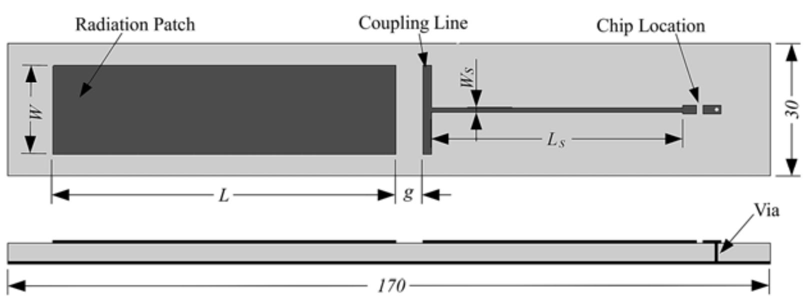

Figure 1. The structure of the basic design, which is designed on a FR-4 substrate with thickness of 3 mm and $\epsilon_r = 4.6$.

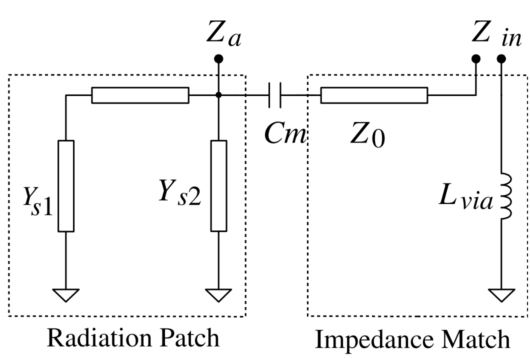

Figure 2. Transmission line model of the basic design.

the coupling line and the coupling edge of the patch. Z_0 is the characteristic impedance of the micro-strip line, and L_{via} accounts for the inductance of the via. The input impedance of the antenna can be calculated as

$$Z_{in} = Z_0 \frac{(Z_a + Z_{C_m}) + Z_0 \tanh(jkL_s)}{Z_0 + (Z_a + Z_{C_m}) \tanh(jkL_s)} + j\omega L_{via} \tag{1}$$

$$= Z_{C_m} \left[\frac{Z_0}{Z_{C_m}} \cdot \frac{\left(1 + \frac{Z_a}{Z_{C_m}}\right) + \frac{Z_0}{Z_{C_m}} \tanh(jkL_s)}{\frac{Z_0}{Z_{C_m}} + \left(1 + \frac{Z_a}{Z_{C_m}}\right) \tanh(jkL_s)} \right] + j\omega L_{via} \tag{2}$$

where, $Z_{C_m} = 1/(j\omega C_m)$, k is the propagation constant of the micro-strip line.

Since the micro-strip line is very thin, the characteristic impedance Z_0 does not change appreciably with variation in the ground plane size. The part of equation xx in the square bracket resembles impedance transformation of $(1 + \frac{Z_a}{Z_{C_m}})$ by a micro-strip line having characteristic impedance of $\frac{Z_0}{Z_{C_m}}$. If Z_{C_m} was sufficiently large, the value of the square bracketed part will be relatively stable with respect to Z_a. This can be achieved by adjusting the gap g between the radiation patch and the coupling edge.

4. SIMULATION RESULTS

The size of the radiation patch can be approximated by the well known transmission line method [16], and then optimized along with the coupling gap g. The length L_s of the micro-strip line can be adjusted to match different RFID chips. A copper sheet of 210 mm × 130 mm is used for the metallic surface where the antenna will be attached.

The simulated $|s_{11}|$ with different gap g are is shown in Figure 3. The two $|s_{11}|$ curve approach each other as g increases. The $|s_{11}|$ difference is within 1 dB when $g = 10$ mm, where the trend is predicted by Eq. (2). The antenna gains, however, are also different when simulated with or without metal. As shown in Figure 4, the gain in the forward direction for the with-metal case is 1.4 dB lower than the without-metal case due to its poorer radiation efficiency. In order to achieve a near identical reading range, $g = 6$ mm was chosen to compensate for the gain difference.

The $|s_{11}|$ values are approximately -5 dB, which corresponds to return loss of -10 dB. Although the $|s_{11}|$ values are high when compared to antennas used in communication or cell phones, it is sufficient for RFID applications. In fact, the reading range of RFID tags is proportional to $\sqrt{1 - |s_{11}|^2}$. A -40 dB tag is only 1.06 times better than a -10 dB tag in terms of reading range. However, very decent RFID tags have reading range only up to 10 or 15 meters, which means that improving the return loss from -10 dB to -40 dB gives a maximum of less than 1 meter reading range improvement. Nevertheless, by introducing additional strip lines or lumped LC network, $|s_{11}|$ values can still be improved. However, additional strip lines will increase the size of the RFID tag, while lumped LC network will largely increase the cost of the tag (the cost for purchasing and soldering them could be more expensive than RFID chip itself).

5. COMPACT DESIGN

The previous basic design resulted in a total length of 170 mm which is impractical. A much compact design based on the same principle is proposed as shown in Figure 5. The micro-strip line used for impedance match is bent along the non-radiation edge of the patch to save space. In order to avoid as much coupling between the transmission line and the radiation patch, the gap g_2 between them is chosen to be much larger than the coupling gap g_1. This compact design results in a 100 mm × 35 mm antenna. The primary dimensions of the compact design are given by $W = 20$ mm, $L = 76.5$ mm, $g_1 = 1$ mm, $g_2 = 5$ mm, $W_s = 1$ mm and $L_s = 42$ mm. The design parameters are optimized to achieve antenna resonance around 915 MHz. The simulated $|s_{11}|$ and radiation pattern are shown in Figure 6 and Figure 7 respectively. Similar to the basic design, the with-metal case is designed to have better impedance match with a gain in the forward direction of the with-metal case is 0.715 dB lower than the without-metal case.

It is notable that the gap g_1 between the coupling line and radiation patch of the compact design is much smaller than the basic design. It is the connecting location between the micro-strip line and the coupling line that caused the difference. In the compact design the micro-strip line is connected to the end of the coupling line to save space, while it is connected to center of the coupling line in the basic design. In the transmission line model analysis, the coupling effect was simplified to be a capacitance C_m. However, the fact is that the coupling line itself also has some inductance and capacitance depending on how we connect to it. If we move the micro-strip line towards one end of the coupling line in the basic design, the gap must also be decreased as in the compact design.

6. PROTOTYPE AND MEASUREMENT

The reading range can be calculated according to the following equation [1]:

$$R = \frac{\lambda_0}{4\pi}\sqrt{\frac{P_{Reader}}{P_{Chip}} \cdot G_{Reader} \cdot G_{Tag} \cdot (1 - |s_{11}|^2)} \tag{3}$$

where, λ_0 is the wavelength in free space. P_{Reader} and G_{Reader} are output power and gain of the RFID reader. G_{Tag} and $|s_{11}|^2$ are the gain and return loss of the proposed antenna. P_{Chip} is the reading sensitivity during reading, which is -18 dBm.

Several prototypes were fabricated with RFID chips bonded to the antennas by both wire-bonding and chip straps, as shown in Figure 8. The reading range tests were performed in the Voyantic$^{\text{TM}}$ tagformance lite [17], which has EIRP of 30 dBm. A copper foil having the size of 210 mm × 130 mm, which is the same as in the simulations, served as the metallic surface. The prototypes are placed on a foam when testing the reading range without metal.

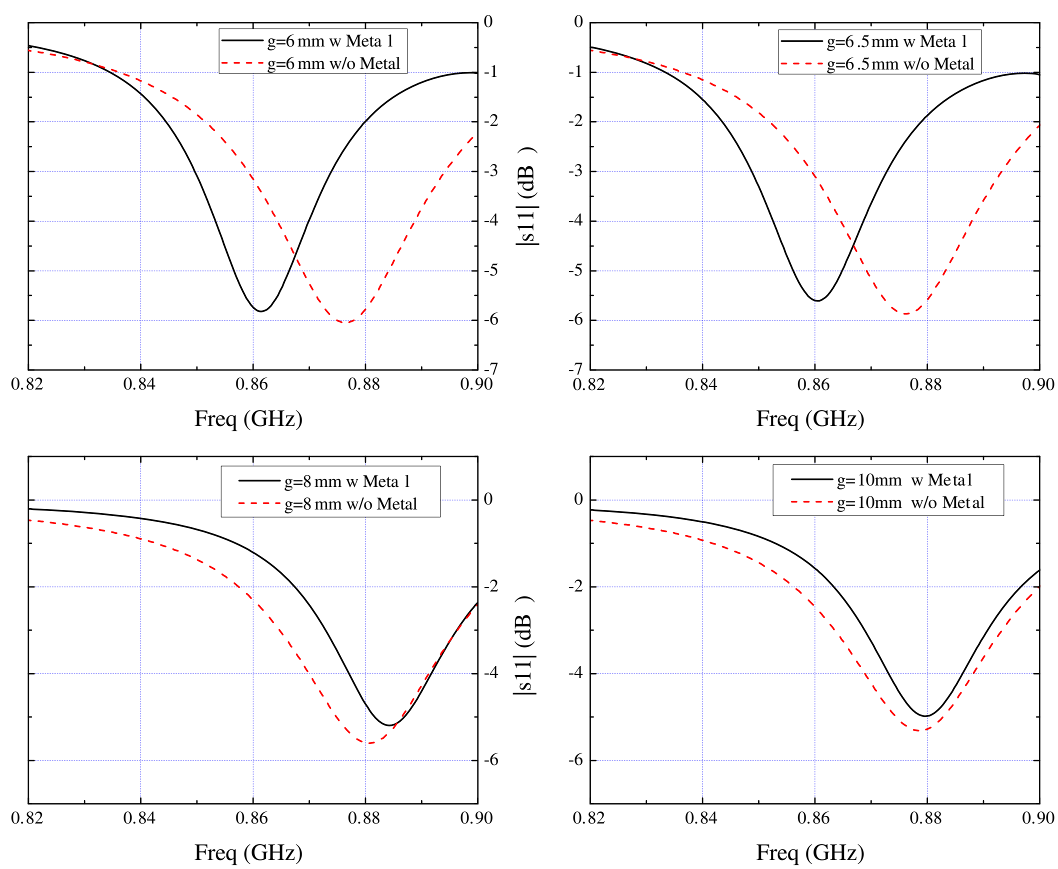

Figure 3. Simulated $|s_{11}|$ of the basic designs with different coupling gap g.

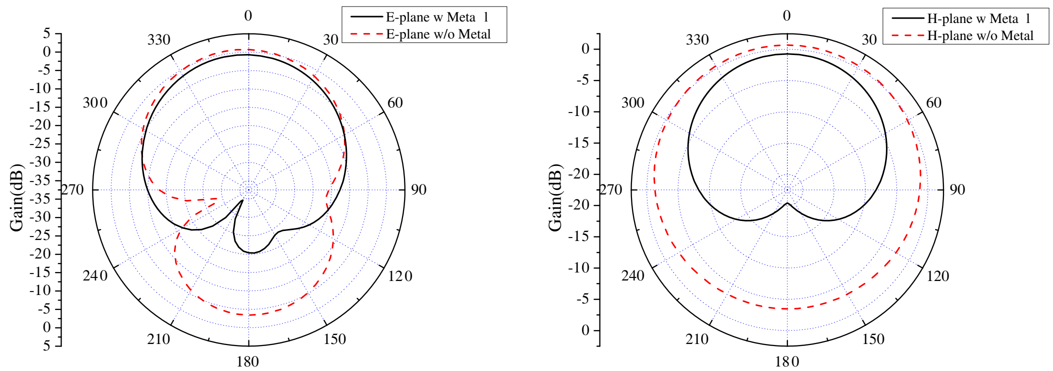

Figure 4. Simulated radiation pattern of the basic design at 865 MHz, when $g = 6$ mm.

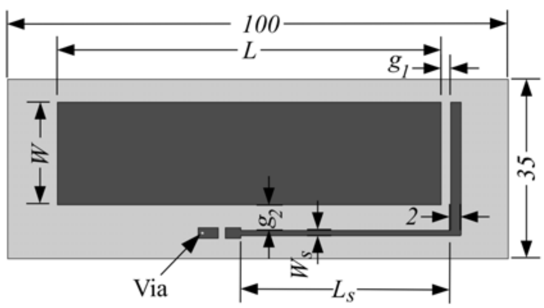

Figure 5. The structure of the compact design, which is designed on a FR-4 substrate with thickness of 3mm and $\epsilon_r = 4.6$.

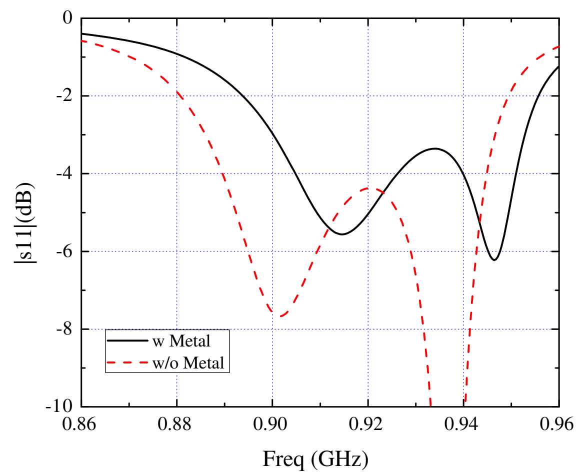

Figure 6. $|s_{11}|$ of the compact design.

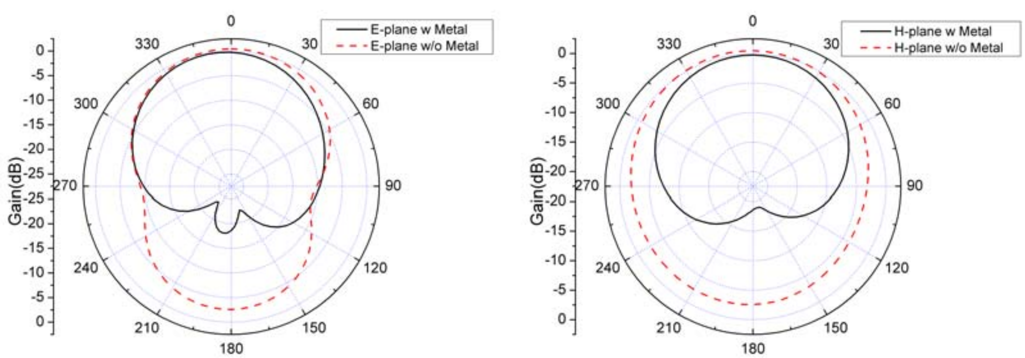

Figure 7. Simulated radiation pattern of the compact design at 915 MHz.

A commercial anti-metal tag was tested with or without the copper foil for comparison, where the ground plane effect can be clearly seen in Figure 9. This commercial tag is SG02-UF101 which was provided by Sygole Co., LTD [18]. It was originally designed for forklift management, and it has a typical patch antenna similar to the one reported in [19]. It was designed to work near 920 MHz, and a reading range degradation of over 50% can be observed when tested without copper sheet.

Figure 8. Photos of the fabricated antennas.

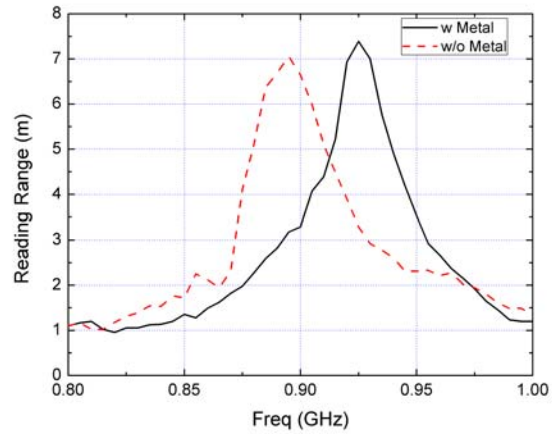

Figure 9. Reading range test of a commercial anti-metal tag.

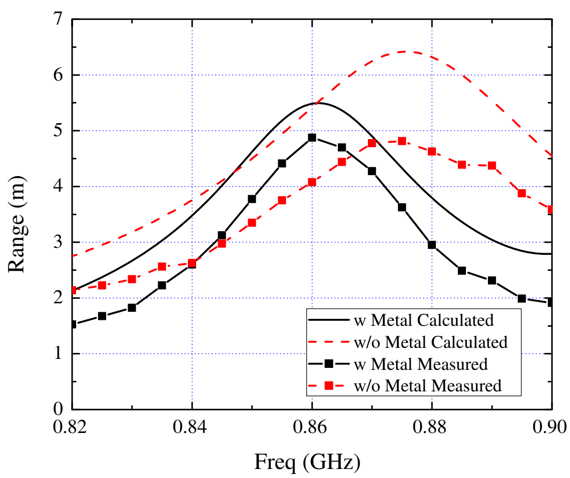

Figure 10. Calculated and measured reading range of the basic design.

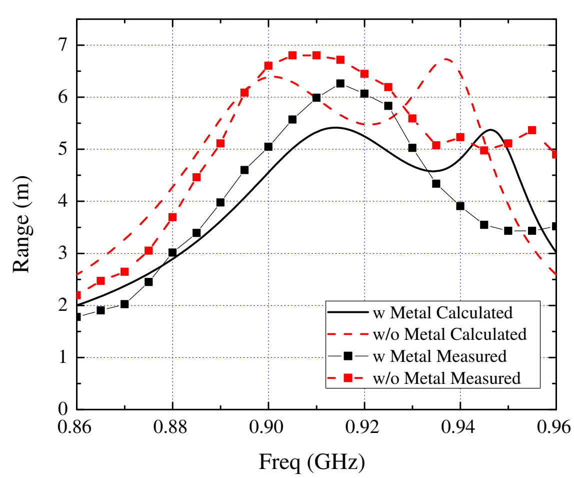

Figure 11. Calculated and measured reading range of the compact design.

The averaged test results of the prototypes are plotted in Figure 10 and Figure 11. Both the calculated results and the measured results show that the proposed antennas have almost the same reading range with or without metal. Although the maximum reading range is a bit less than the commercial tag, both the basic design and the compact design have much better bandwidth and the reading range degradation has been significantly improved. The differences between the calculated results and the measured results are partly because the antenna gain of a single frequency is used instead of the gain in the whole band. The antenna gain in the frequencies other than the designed frequency are lower, which could be predicted theoretically or from simulation.

7. CONCLUSION

The paper presented a design of capacitively coupled patch antenna for RFID tags that has near identical reading range when placed on metal or non-metal surfaces. The measurements have validated the effectiveness of the proposed design method. Although our measurements are limited to with or without metal cases, the proposed antennas works on all kinds of materials as long as Equation (2) hold. The compact design has much wider bandwidth compared to the basic design, which is probably caused by the coupling between the micro-strip line and the non-radiating edge of the patch. 3 mm substrate was used in our design, which is good for vehicle or pallet management, it might be too thick for asset management such as handheld tools or computers. Thinner antennas can be easily designed with the same method, although bandwidth and radiation efficiency might be compromised.

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