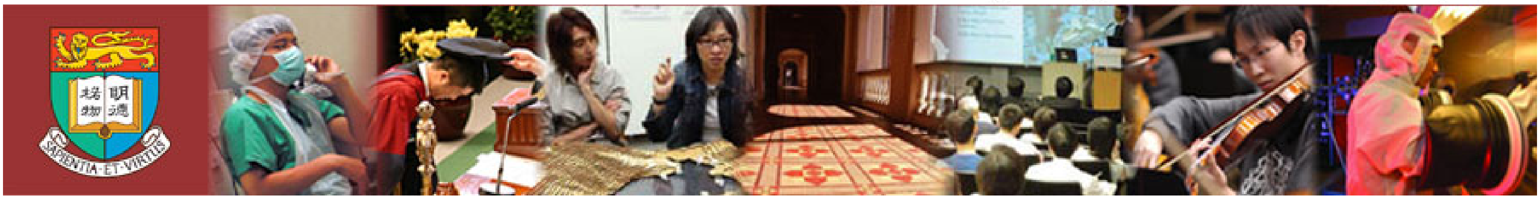

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Compact Metallic RFID Tag Antennas With a Loop-Fed Method

Peng H. Yang, Yan Li, Lijun Jiang, *Member, IEEE*, W. C. Chew, *Fellow, IEEE*, and Terry Tao Ye

***Abstract*—Several compact, low profile and metal-attachable RFID tag antennas with a loop-fed method are proposed for UHF RFID systems. The structure of the proposed antennas comprise of two parts: (1) The radiator part consists of two shorted patches, which can be treated as two quarter-wave patch antennas or a cavity. (2) A small loop printed on the paper serves as the feeding structure. The small loop provides the needed inductance for the tag and is connected to the RFID chip. The input impedance of the antenna can be easily adjusted by changing loop dimensions. The antenna has the compact size of 80 mm $\times$ 25 mm $\times$ 3.5 mm, and the realized gain about-3.6 dB. The measured results show that these antennas have good performance when attached onto metallic surfaces.**

***Index Terms*—Compact antenna, feeding network, low profile, metallic surface, RFID tag antenna.**

I. Introduction

RADIO FREQUENCY identification (RFID) tag has been widely used recently in supply chain and logistics applications to identify and track goods. Tag antenna is one of its key technologies. In order to reduce the cost, most existing RFID systems use modified dipole antennas as tags; these dipole-type antennas can be printed on paper or plastic materials and then pasted on products. They have the merits of small size and are easy to fabricate. However, dipole-type antennas are sensitive to the environment due to their omni-directional radiation characteristics [1], [2]. For example, dipole antennas often show high performance when pasted on paper or plastic boxes, but they do not work when pasted on metal surfaces or bottles with liquid in it.

Microstrip antenna is a good choice for metal-attachable RFID tags because of the ground plane in its structure. In [3], the author investigated the performance of microstrip-type tag antennas using the cheapest dielectric FR4 as substrate. These antennas are easy to fabricate but are large in size. Hence, it is unsuitable for RFID tag applications. In [4], a compact microstrip antenna with some slots loaded is proposed. Also, a simple feeding structure is used and the input impedance can be adjusted easily by changing the length of the feeding line alone. However, this structure requires a via-hole to connect the patch and the ground, which increases the fabrication cost. In [5], [6], patches are fed by a small loop. The merit of this inductively coupled feeding technique is that the imaginary part of the input impedance can be easily changed by tuning the loop size and the distance between the loop and the patches. In order to further reduce the size, the planar inverted-F antenna (PIFA) is also proposed for RFID tag antenna designs [7]. However, because PIFA antennas often need coaxial probe feedings, this type of structure requires embedding the RFID chip vertically between the ground plane and the radiation patch. Hence, it is difficult to fabricate. In [8], [9], the authors proposed to use a slot or aperture antenna as the radiator. A RFID chip is put on the center of the slot as the feeding source. In [10], the RFID chip is connected to a small dipole as a coupling source of the slot. The input impedance of this tag can be adjusted by changing the location of the small dipole. The shortcomings of these slot-type antennas are their size seem still large for RFID tags.

Recently, many people consider using artificial magnetic conductor (AMC) or electronic band gap (EBG) structures for tag antenna designs. Because these new artificial structures have the character of zero-reflection phase, the dipole-type tag antenna can be put very close to them. In [11], a dipole is put on a 5×3 AMC plate as the tag antenna. This antenna has the advantage of the high gain (about 4.5 dB) but the drawbacks of large size and high cost. It is suitable for reader antennas instead of tag antennas. There are some other compact and low-profile AMC structures [12], but the complicated structures and narrow bandwidth (just a few megahertz) limit its application.

Most RFID tags are disposable, which is acceptable for dipole-type antennas because of their low cost. However, for microstrip-type antennas, disposable designs will lead to a big waste. The microstrip-type antennas introduced above have relatively higher cost compared to dipole-type tags. Meanwhile their structures are unchangeable, implying that a fixed structure can only be used for one RFID chip. If we want to replace the chip, the entire antenna must be re-designed and re-fabricated. Therefore, a simple, reusable microstrip antenna is attractive for low-cost metal-attachable RFID systems.

In [13], we have proposed an idea for the reusable microstrip tag antenna design. This antenna shows good performance when

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attached on metallic objects. But the physics of its feeding structure was not very clear and the size was relatively large. In this paper, several compact structures are proposed, analyzed and tested. In Section II,the motivation and principle of the design are introduced. Then, in Section III, several key parameters of the structure are analyzed and discussed. In Section IV, prototypes are fabricated and tested. This kind of designs is summarized in Section V.

II. Antenna Design

Two issues motivated us to design a flexible feeding structure for low cost metallic RFID tags: First, unlike conventional 50 Ohms antennas, RFID tag antenna has complex input impedance because it should be a conjugate match to the RFID chip. There is no unified standard for RFID chips. Different chips have different impedance. It is impossible to design an antenna that can match all kinds of chips. Second, most tag antennas are disposable design because the information in the chip is unique for a certain product. If the chip is integrated into the antenna, the antenna can be used only once.

For the reasons mentioned above, we propose to design the feeding network and the radiator separately. The radiator consists of two symmetrical patches, which are mounted on a dielectric substrate. One edge of the patch is shorted to the ground, and there is a gap between the two patches. This gap is the radiating slot. The radiator part can be seen as two quarter-wave patch antennas sharing a common radiating slot, or a cavity with a slot loaded. For traditional patch antennas, whose radiating slots are on the side edges of the patch, the ground is usually larger than the patch. The advantage of our design is to move the radiating slots from the edge to the center, which can reduce the total size of the antenna effectively.

The coaxial probe can be put at a proper location of one of the two patches to feed this structure [14], [15]. Then this patch is regarded as the primary patch. Another one is the parasitic patch. This is the simplest feeding method. Unfortunately, it is not suitable for the RFID tag antenna. Another problem is that the parasitic patch has a phase delay compared to the primary patch due to the asymmetric feeding. To feed two patches simultaneously, we can connect the two patches directly by a RFID chip [8], [9], [16], [17]. This is straightforward but has some drawbacks, such as the inflexibility and difficulties of impedance matching.

A feeding method of putting a small dipole on the top of the gap is proposed to feed the structure [10], [13]. The length of the dipole is far less than the operating wavelength of the antenna. To couple more energy into the cavity, the dipole should be put very close to the slot $(d \ll \lambda_0)$. This structure can be regarded as a cavity-backed slot antenna. If the dimension of the cavity is designed properly, TM_{10} mode will be excited and resonate in the cavity. The dipole and the cavity have a strong coupling at the resonant frequency, and then the energy can be transformed from the dipole to the cavity through the slot.

Usually, the input impedance of a RFID chip has a small real part and a large negative imaginary part (capacitive). Hence, for conjugate matching, a loop (inductive) antenna is preferred than the small dipole as the feeding network. The geometry of the proposed loop-fed antenna is shown in Fig. 1(a).

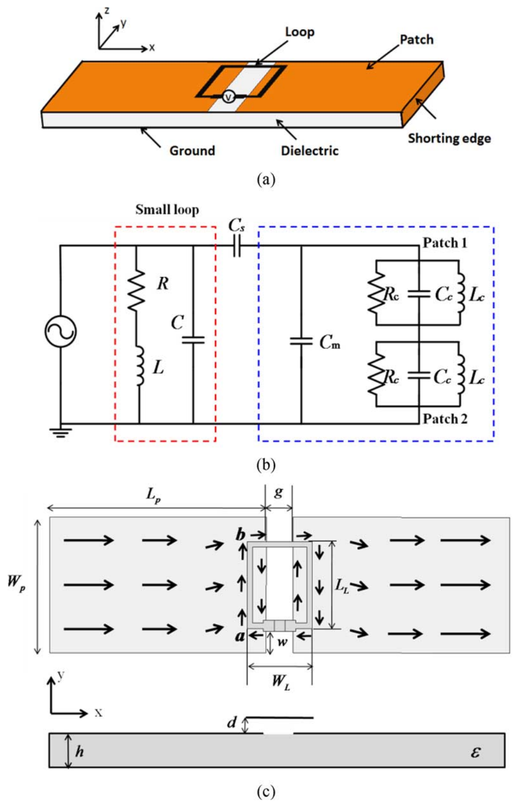


Fig. 1. A small loop put on a pair of shorted patches. (a) The geometry. (b) Equivalent circuit with $R = 0.3$ ohms, $L = 24$ nH, $C = 0.02$ pF, $C_s = 0.15$ pF, $C_m = 0.2$ pF, $R_c = 850$ ohms, $C_c = 7.7$ pF and $L_c = 4$ nH. (c) Antenna parameters and current distribution on the patches with $L_p = 39$, $W_p = 25$, $g = 5$, $L_L = 16$, $W_L = 12$, $w = 4$, $d = 0.5$ and $h = 3$. The strip width of the loop is 1 (all dimensions are in mm).

Fig. 1(b) shows the equivalent circuit of the antenna. To model the small loop, a capacitance C is put in parallel with resistance R and inductance L. The capacitance C accounts for the distributed capacitance between the sides of the loop. Note that a loop with an uniform current distribution would have no capacitance, since there would be no charge along the conductor of the loop. For the loop-fed structure, if the loop is extremely small, the x component current on the loop have the same magnitude but opposite directions so they cancel each other. Hence, the cavity cannot be excited in this case. However, when the loop becomes larger and larger, the x component current have different magnitude and opposite directions. Hence, there is a net current along the x axis. This net current looks like an electric dipole and can be used as the excitation source. The resistance R and inductance L of the small rectangular loop can be estimated approximately by [1], [21]

$$R = 20\pi^2 \left(\frac{P}{\lambda}\right)^4 (P < \lambda/3) \tag{1}$$

$$L = 0.4(L_L + W_L) \ln \left[\frac{2L_L W_L}{s(L_L + W_L)}\right] (\mu\mathrm{H}) \tag{2}$$

where P is the perimeter of the loop and s is the width of the loop strip.

Because the thickness h of the cavity is very thin, according to the cavity model [18], [19], the two quarter-wave patch antennas (or cavity) can be represented as two parallel circuits. The capacitance C_c of the patch can be estimated roughly by using the parallel plate wave guide model [2]

$$\sqrt{\frac{L_c}{C_c}} = Z_{\text{parallel plate}} \approx \eta \frac{h}{W_p} \tag{3}$$

where $\eta = \sqrt{\mu/\varepsilon}$ is the intrinsic impedance of the medium between the parallel plates. Because the resonant frequency is $\omega_{\mathrm{r}} = 1/\sqrt{L_c C_c}$, we can obtain

$$C_c = \frac{W_p}{\omega_r \eta h} = \frac{2\varepsilon W_p L_p}{\pi h} \tag{4}$$

here we suppose that $L_p = \lambda_g/4$ and λ_g is the guided wavelength in the cavity. Through (3) and (4), the equivalent capacitance C_c and inductance L_c of each patch are 7.7 pF and 4.0 nH, respectively. The radiation resistance R_c of single patch can also be estimated using cavity model. Since the energy is coupled from the gap into the cavity, the location of feeding point in cavity model should be chosen close to the gap (the radiation edge). The estimated resistance R_c is about 850 ohms.

The capacitance C_m can be estimated approximately by [20]

$$C_m = \frac{\varepsilon W_p}{2\pi} \left\{ \ln \left[0.25 + \left(\frac{h}{g} \right)^2 \right] + \frac{g}{h} \tan^{-1} \left(\frac{2h}{g} \right) \right\} \tag{5}$$

If the width of the gap $g = 5$ mm, then $C_m = 0.14$ pF. Note that these parameters are just approximate values. When the small loop is put close to the patches, these values would change due to the coupling between the loop and the patches. It is very hard to determine these values analytically if coupling effects are taken into consider. But they can be extracted by comparing the results of circuit model and full wave method (Volume Surface Integral Equation codes developed by our group). After a little bit tuning, the precise values of C and C_m as well as the coupling capacitance C_s can be determined and the results of circuit model can match well to the full wave results. The ultimate parameters of these lumped elements and the antenna are given in Fig. 1(b) and (c), respectively. The input impedance of full wave method and equivalent circuit models are shown in Fig. 2. Good agreement is achieved.

To evaluate the performance of the proposed antenna when mounted on metallic objects, we pasted this loop-fed tag antenna on a 200 mm × 200 mm metallic plate. The dielectric has a relative permittivity of 4.2 and loss tangent of 0.02. The medium between the small loop and the cavity was set as air to simplify the simulation. Fig. 3(a) is the gain pattern of the antenna. The simulated maximum realized gain is about −0.7 dB near 915 MHz, which is enough for most low-cost RFID tags. The current distribution on the loop and the patches are shown in Fig. 3(b). Note that the current at point "a" and point "b" are not symmetrical. Just as the current direction shown in Fig. 1(c), at point "a", the x component of the current have the opposite direction. Hence they cancel each other. However, at point "b", the current have the same direction then add together.

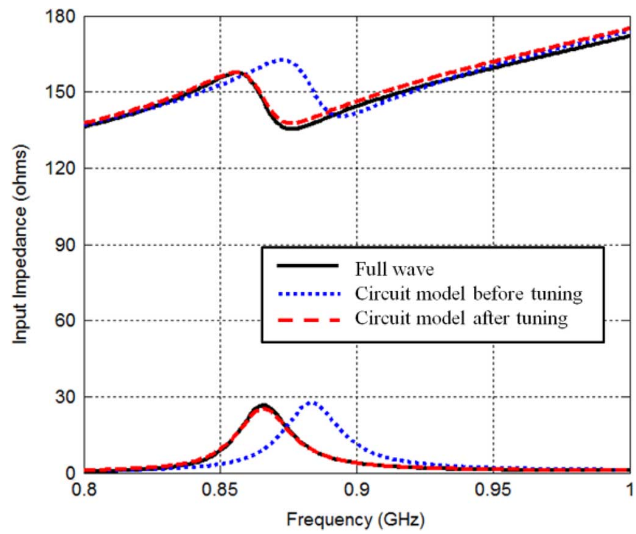
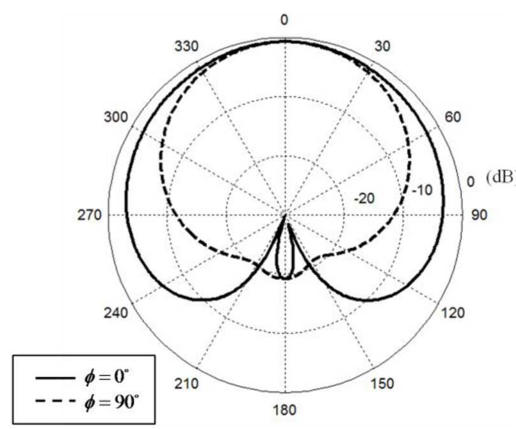
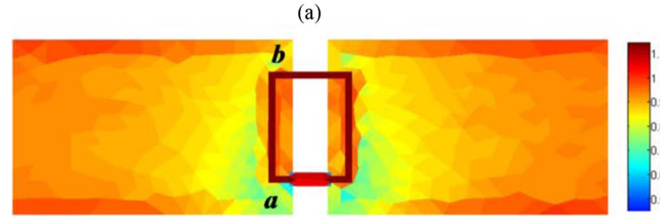


Fig. 2. Simulation results of full wave method and equivalent circuit model for the loop-fed antenna.



(a)



(b)

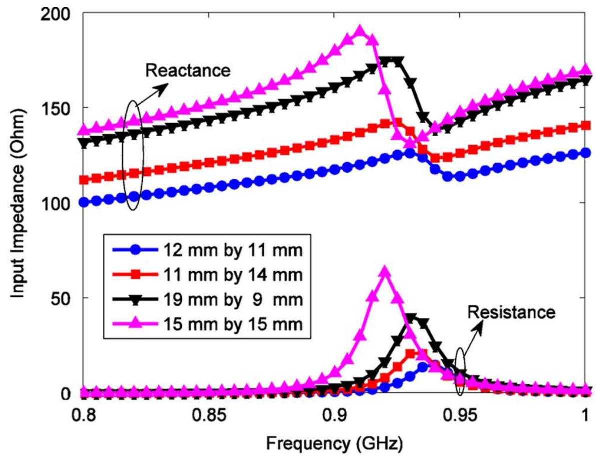
Fig. 3. Performance study of the proposed loop-fed antenna. (a) Gain pattern of the proposed antenna at 915 MHz. (c) Current distributions at 915 MHz.

III. Parameters Study

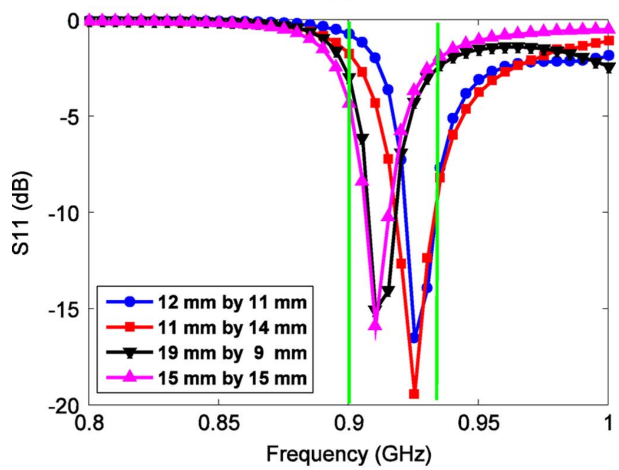
In this section, we focus on several key parameters of the structure to see their effects to the performances of the antenna. These parameters include: The loop size $L_L \times W_L$, the distance w between the loop and the edge of the patches and the gap g between the two patches. In all simulations, the tags were supposed to be mounted on a 200 mm × 200 mm metallic plate.

A. Loop Size $L_L \times W_L$

Our goal is to design a separable feeding network which can match different RFID chips by changing the size or structure



(a)



(b)

Fig. 4. Input impedance and S_{11} for different loop size. (a) Input impedance. (b) S_{11}. The blue line to match the RFID chip with impedance of $6 - \mathrm{j}127$ at 915 MHz, the red line to $13 - \mathrm{j}140$, the black line to $7 - \mathrm{j}170$ and the pink line to $30 - \mathrm{j}200$. Other parameters are: $L_p = 39$, $W_p = 25$, $g = 5$, $d = 0.5$ and $h = 3$. The strip width of the loop is 1 (all dimensions are in mm).

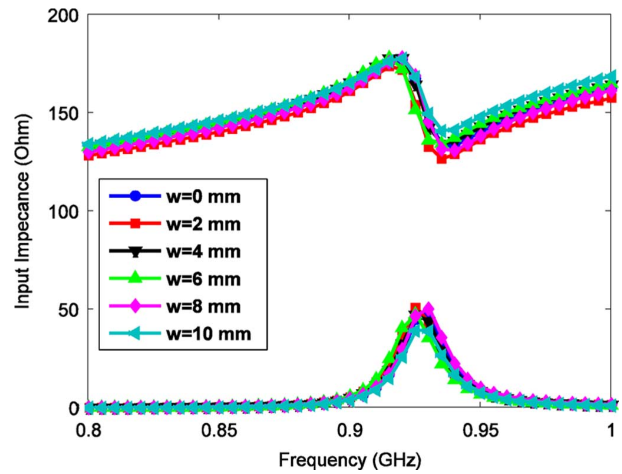


Fig. 5. Input impedance for different value w. The loop size was fixed at 14 mm$\times$14 mm. The parameter w was changed from 0 mm to 10 mm.

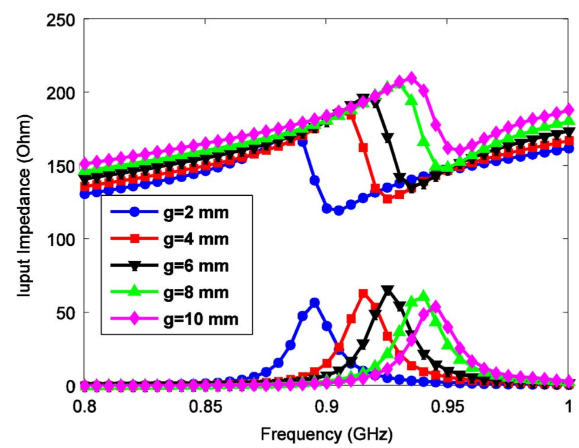


Fig. 6. Input impedance for different g. The loop size was fixed at 14 mm $\times$ 14 mm. The parameter g was changed from 2 mm to 10 mm.

of the feeding network while keeping the radiator part unchanged. To simplify the problem, we fixed others parameters and adjusted the loop size $L_L \times W_L$ only. Four types of RFID chips were chosen to do the simulation. Around 915 MHz, their impedance are: $6 - \mathrm{j}127$ [22], $13 - \mathrm{j}140$ (Alien-H2), $7 - \mathrm{j}170$ [23] and $30 - \mathrm{j}200$ (Alien-H3). To make this tag work in the north American frequency range (from 900 MHz to 930 MHz) with these chips, we can change the loop size $L_L \times W_L$, the results are shown in Fig. 4.

Fig. 4(a) are the input impedance of the tag with different loop size: The blue line is to match the RFID chip with impedance of $6 - \mathrm{j}127$ at 915 MHz, the red one is to $13 - \mathrm{j}140$, the black one is to $7 - \mathrm{j}170$ and the pink one is to $30 - \mathrm{j}200$. It was found that with the perimeter of the loop becomes larger and larger, the resonance becomes stronger. Also, the resonant frequency tends to become lower because big loop will induce a large net current along the x axis, which is equal to the increase of the coupling capacitance C_s. From circuit theory, it will decrease the resonant frequency. Fig. 4(b) shows the S_{11}. It can be seen that all of the four RFID chips can be matched well within the operating frequency range.

It is worth to say that in this example, to change the input impedance, we only adjusted the loop size. Hence, the freedom is very limited. To add more freedoms into the feeding network, more complex feeding network structures, such as the T-mach or Gamma-match [1] can be designed, and then more RFID chips might be matched.

B. The Distance w Between the Loop and the Edge of the Patches

In all of the aforementioned examples, the loops were put at the center of the slot. In fact, the location of the loop is not sensitive to the input impedance. To approve this, we fixed the loop size $L_L \times W_L$ at 14 mm $\times$ 14 mm, other parameters were the same to last example except w. Then w was changed from 0 mm to 10 mm. It is clear to see from Fig. 5 that the parameter w will not affect the input impedance.

C. The Gap g Between the Two Patches

In this example, we analyzed the effects of parameter g to the input impedance. Similar, we fixed the loop size at 14 mm $\times$ 14 mm, other parameters are the same to last two examples except

Fig. 7. The fabricated prototype of the loop-fed double patches antenna, the total dimension is 80 mm × 25 mm × 3.5 mm.

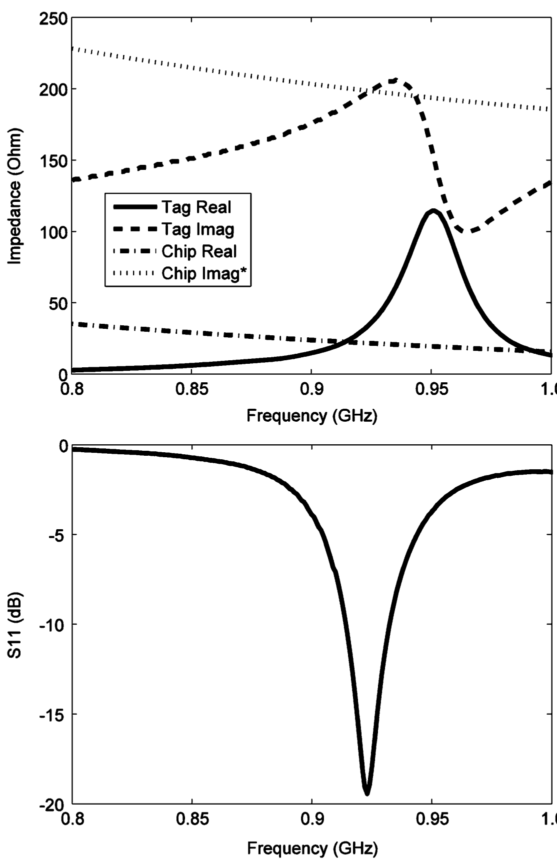
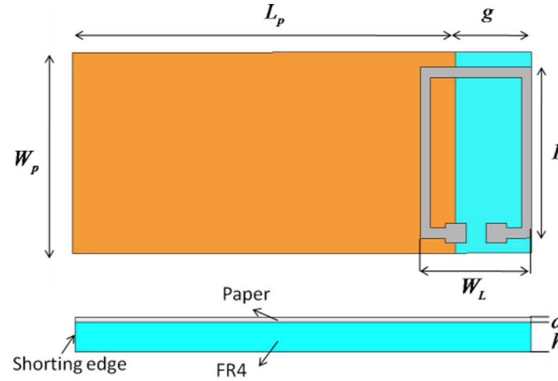
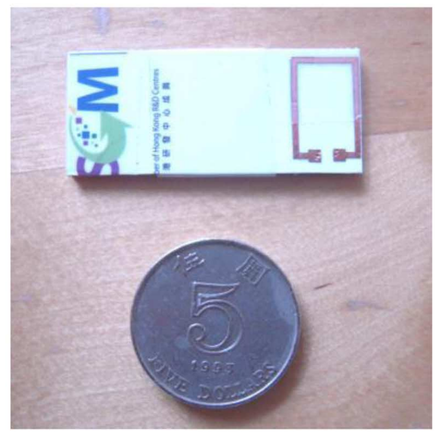


Fig. 8. The input impedance and S_{11} of the loop-fed double patch antenna (Type A). The antenna was put on a 200 mm × 200 mm metallic plate.

g. It is found in Fig. 6 that with the value of g decreases, the resonant frequency becomes lower. The reason can be explained as follow: The center of the antenna can be regarded as a virtual ground and the capacitance C_m can be seen as the sum of two open ended capacitances (the capacitance between the radiating edge of the patch and the virtual ground). The length L_p of the patch will be a little bit shorter than quarter-wave dielectric length because the open ended capacitance effects. When g decreases, the two open ended capacitances will increase. It means for the same resonant frequency, the patch length L_p looks more shorter, or, for the same length L_p, the resonant frequency looks more lower. Though small value of g can reduce the total size of the antenna, it will also decrease the gain because of the strong mutual coupling between the two patches. Hence, g cannot be set too small.



(a)



(b)

Fig. 9. The loop-fed single patch antenna. The total dimension is 45.5 mm × 20 mm × 3.5 mm. (a) The geometry. (b) The prototype.

IV. Fabrication and Measurements

The advantage of the proposed idea is that the feeding network and the radiator can be designed separately. From the discussion above, the working mode of the antenna is determined by the resonant mode of the cavity. If we choose the size of the cavity properly, the antenna can work well at the TM_{10} mode. On the other hand, the feeding structures can be used as the excitation and impedance matching network. Different feeding structures will affect the input impedance significantly. This gives us an inspiration to design a disposable feeding network for tag antennas. This feeding structure should be simple, easy for fabrication and low cost.

In the aforementioned examples, in order to simplify the simulation, we use the air as the substrate between the feeding network and the patches. In practice, we should find a proper material as the substrate. Paper is a good choice because it is very cheap and easily available. The most important point is that it is easy to print feeding circuits on the paper by using the conductive ink or copper foil. In our designs, we use some common paper, such as those used for name cards, as the substrate. The estimated relative permittivity constant of the paper is around

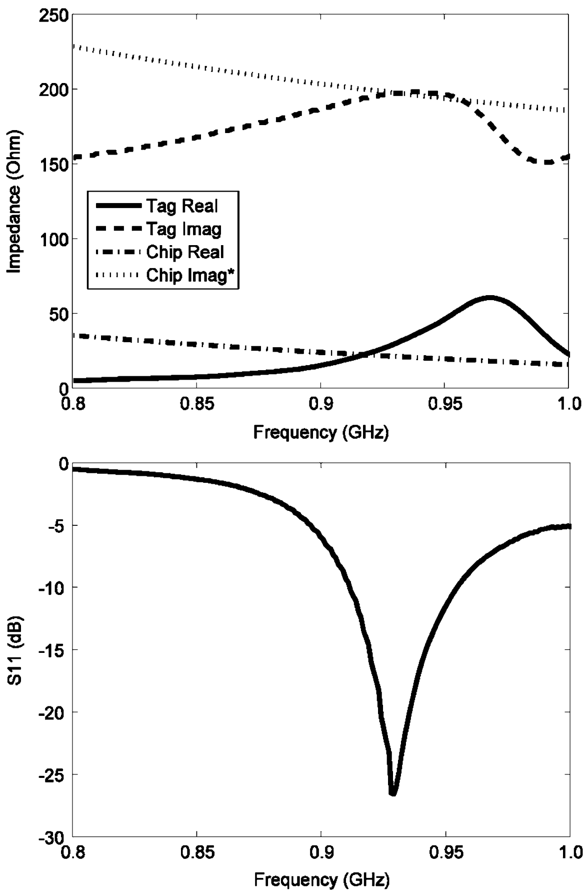
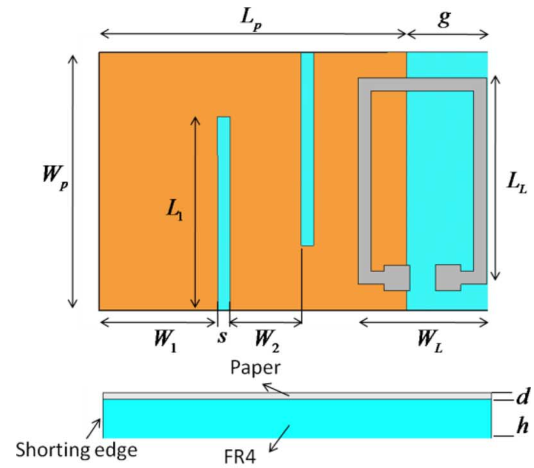
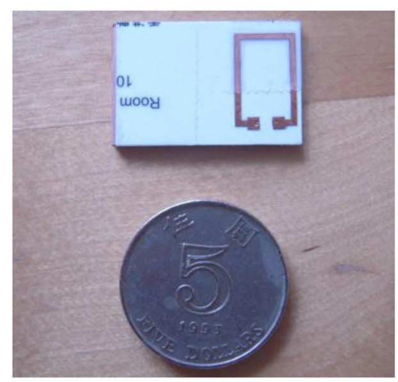


Fig. 10. The input impedance and S_{11} of the loop-fed single patch antenna (Type B). The antenna is put on a 200 mm × 200 mm metallic plate.



(a)



(b)

Fig. 11. The loop-fed single patch antenna with slots loaded. The total dimension is 30 mm × 20 mm × 3.5 mm. (a) The geometry. (b) The prototype.

3.2–3.5 [24], and the loss tangent is about 0.08. The drawback of paper is its high loss. But it is acceptable for tag antennas because the read range requirement of most passive RFID tag applications are just few meters.

A. Loop-Fed Double Patch Tag Antenna (Type A)

The loop-fed double patch antenna was fabricated and tested. The fabrication prototype is shown in Fig. 7. The antenna used the Alien's RFID chip, whose impedance is about 30–200j at 915 MHz. The dielectric in the cavity is FR4. Its measured permittivity is about 4.2 and loss tangent is about 0.02 [10], [17]. The parameters of the antenna are (all in mm): $L_p = 35$, $W_p = 25$, $g = 10$, $L_L = 14$, $W_L = 12$, $w = 5$, $d = 0.5$ and $h = 3$. The strip width of the loop is 1 mm. With the method proposed in [25], [26], the antenna was measured through the Agilent's four ports vector network analyzer. Fig. 8 shows the input impedance and S_{11} of measured results. This tag antenna was mounted on a 200 mm × 200 mm metallic plate. It is clear to see that the antenna can match well around 920 MHz.

B. Loop-Fed Single Patch Tag Antenna (Type B)

The antenna proposed above has a symmetrical structure: The cross section (yz plane) at the center of the antenna can be seen as a perfect electric conductor (PEC), see Fig. 1. Hence, it is possible to split the antenna along yz plane to reduce the total dimension. Fig. 9(a) shows the geometry, where $L_p = 45.5$, $W_p = 20$, $g = 7.5$, $L_L = 17$, $W_L = 11$, $d = 0.5$ and $h = 3$ (all in mm). The width of the loop strip is 1 mm. Fig. 9(b) is the prototype. Fig. 10 is the measured input impedance and S_{11} of this antenna when mounted on a 200 mm × 200 mm metallic plate. Here the FR4 has a relative permittivity about 4.2 and loss tangent about 0.04. The paper is the same as Type A. It can match well around 925 MHz by adjusting the parameters carefully.

C. Loop-Fed Single Patch Tag Antenna With Slots Loaded (Type C)

In order to further reduce the size of the tag, two slots were added on the patch. These slots can bend the patch surface current paths to achieve a lower fundamental resonant frequency. The geometry and prototype of the compact tag antenna are shown in Fig. 11(a) and (b), respectively. The parameters in Fig. 11(a) are: $L_p = 24$, $W_p = 20$, $g = 6$, $L_L = 16$, $L_1 = 15$, $W_1 = 9.25$, $W_2 = 5.5$, $W_L = 10$, $s = 1$, $d = 0.5$ and $h = 3$ (all in mm). The width of the loop strip is 1 mm. The parameters of FR4 and paper are the same as Type B. The measured results of the compact antenna mount on a 200 mm × 200 mm metallic plate are shown in Fig. 12. From the results we can see that it can match well around 915 MHz.

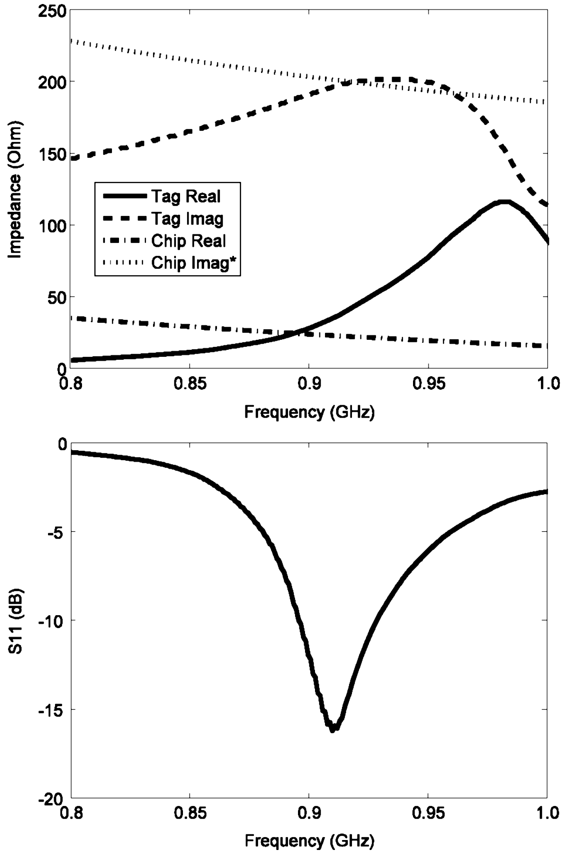


Fig. 12. The input impedance and S_{11} of the loop-fed single patch antenna with slots loaded (Type C). The antenna is put on a 200 mm × 200 mm metallic plate.

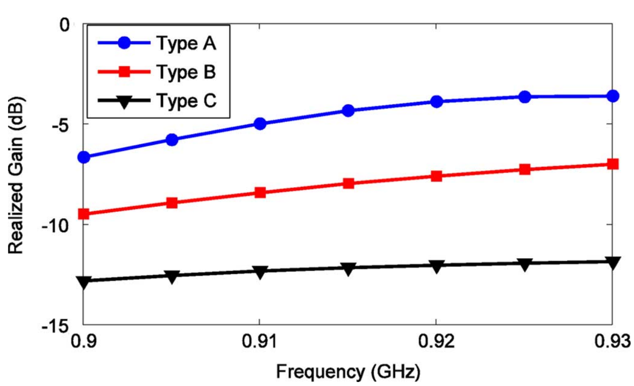


Fig. 13. The simulated realized gain of the three type tag antennas (The antennas are put on a 200 mm × 200 mm metallic plate).

D. Read Performance and Comparisons With Other Tags

The realized gains of these tags were also investigated and the results are shown in Fig. 13. The maximum gain within the operating frequency rang are −3.6 dB, −6.9 dB and −11.8 dB for Type A, Type B and Type C, respectively. The main reason for the low gain is due to the high loss of the paper we used.

The read ranges of these prototypes were tested using Impinj reader IPJ-R1000. The operating frequency hops from 900 MHz to 930 MHz. We fixed the output power to 30 dBm and measured the read distances of these tags (summarized in Table I). These antennas have a good performance when mounted on metallic objects but poor performance in free space because the small ground will lead to a large back radiation. Also, the resonant frequency in free space would be lower than the case when they are mounted on a large metallic plate. Finally, we compared our tags with other designs. In [17], the structure is very similar to ours but with a direct feeding method. The gain of [17] is about −6.4 dB and the maximum read range is 3.1 meter when mounted on a $0.5\lambda \times 0.5\lambda \times 0.01\lambda$ metallic sheet. In [27], the maximum read range of the commercialize tag can reach 7 meter when mounted on a 300 mm × 300 mm metallic plate. The performance of [27] is very good but also with the drawback of large assembled size: 9.45 cm × 7.2 cm × 1 cm.

TABLE I
READ RANGE OF THE PROPOSED ANTENNAS

	Type A	Type B	Type C	Ref. [17]	Ref [27]
Free space	3 m	1.4 m	0.5 m	—	—
Metallic objects	5 m	2.5 m	1 m	3.1 m	7 m

V. CONCLUSION

A type of loop-fed compact UHF band RFID tag antennas for metallic objects is presented in this paper. These antennas use the quarter-wave patch structure (or a cavity) as the radiator and a small loop as the feeding network. The cavity determines the resonant mode while the feeding part is adjustable to match the required input impedance. The feeding network and the radiator are designed separately. The feeding part is simple with the low cost. It can be printed on paper using some copper foil or conductive ink. Hence, it is a disposable design. Thanks to the separable idea, the radiator part (the quarter-wave structure) can be used many times for different RFID chips or feeding networks, which will lower the total cost of metallic tag antennas. Three designs are proposed. The smallest one has the size of 30 mm × 20 mm × 3.5 mm, which is just 1/10 wavelength in free space. The merits of their compact, low cost, and metal-attachable properties make the proposed antennas well suitable for packaging RFID applications with metallic objects.

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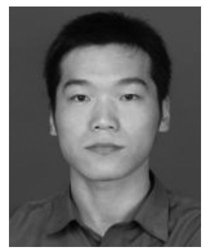

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