

Magnetic Substrate Folded Dipole Antenna for UHF RFID Metal Tag

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Abstract—In this paper, magnetic material was applied in the design of a UHF-RFID metal tag to increase the reading distance. The influence of the electromagnetic properties, especially the electromagnetic loss, of magnetic substrate on the gain of the tag antenna is discussed by analyzing the reflection and the surface current distribution. As to folded antenna, the loss of energy caused by the magnetic substrate tends to occur in the folding edge of the antenna. Both simulations and experiments indicate that electromagnetic loss markedly reduces the gain rapidly when both the dielectric loss tangent ($\tan \delta$) and the magnetic loss tangent ($\tan \delta m$) are between 0 and 0.3. The reading distance drops from 3 m to 1.5 m when the $\tan \delta m$ of the magnetic composite substrate increases from 0.009 to 0.023. And $\tan \delta m$ should be less than 0.1 for the antenna working excellently. The conclusion offers meaningful guidance for future studies of magnetic substrate folded metal tag.

1. INTRODUCTION

With the increasing use of radio frequency identification (RFID) in the ultra-high frequency (UHF: 860–960 MHz) band, the RFID tag has gained much interest in supply chain management, and mounted on metallic surface. However, normal RFID tag antennas cannot work properly or even unable to read on the surface of metallic objects because of the destructive interference of electromagnetic waves [1]. Much research about metal tag antennas has been reported to solve this problem. The main solutions include inserting a dielectric layer between the antenna pattern and the metal ground or even using special antenna design principles to avoid metal interference [2–6], but their uses are limited by the considerable prices. Recently, a series of novel RFID metal tags is proposed, for instance, tag equipped with Artificial Magnetic Conductor reported by M. Abu et al. [7], and tag equipped with magnetic composite material reported by Kuo et al. [8]. The use of magnetic substrate opens up opportunities for solving metal interference problem. Besides, permeability and flexibility of magnetic composite materials make it possible to develop a miniaturized and flexibility RFID tag. However, there is a lack of dedicated investigation about the effects of the electromagnetic properties of magnetic material on the tag performance, especially concern with the electromagnetic loss.

In this paper, we attempted to study the effects of magnetic substrate on the UHF RFID tag. ‘Folded’ and ‘inverted-F’ structures have been commonly used to reduce the size of RFID tags, since the tags have to be attached onto small objects [9]. So we presented a passive folded dipole antenna with magnetic substrate placed on metal surface. The folded dipole antenna with magnetic substrate is modeled and simulated by using the software HFSS to analysis the influence of electromagnetic properties to the antenna performance. Experimental verification is also conducted.

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2. ANALYSIS OF ANTENNA PARAMETERS

In passive UHF RFID systems, the energy needed for communication is supplied entirely from the reader device, and the method for data transmission between the tag and the reader is backscattering. In the communication system, read range is one of the most important characteristics of the tag. The theoretical maximum read range r_{tag} depends on the power reflection coefficient and can be calculated using the Friis free-space formula as [10]:

$$r_{tag} = \frac{c}{4\pi f} \sqrt{\frac{\text{EIRP}}{P_{th}} * \tau * G_{tag}}. \quad (1)$$

where c is the speed of light, and f is the frequency, and EIRP is the effective power transmitted by the reader, and P_{th} is the minimum threshold power necessary to power up the chip, and G_{tag} is the gain of the receiving tag antenna (G_{tag} is the product of the directivity and the radiation efficiency). The factor τ is the power wave transmission coefficient. When the reader is selected, the effective power (EIRP) transmitted by the reader to the tag is determined. The power obtained by the tag is used to turn on the chip and to perform back-scattering modulation. When the chip is selected, the minimum power (P_{th}) needed to turn on the chip and its impedance are determined. The reading range increases as the increasing of EIRP, G_{tag} , and τ ; but decreases with the increasing P_{th} . τ can be written as

$$\tau = 1 - |S_{11}|^2 = 1 - \left| \frac{Z_a - Z_{chip}^*}{Z_a + Z_{chip}} \right|^2. \quad (2)$$

where S_{11} is the reflection coefficient at some frequency; Z_a represents the antenna impedance; Z_{chip} represents the IC impedance with Z_{chip}^* being its conjugate. Obviously, large G_{tag} and impedance matching are required to obtain long read distance. The impedance matching would be broken by a conductor plane placed close to the tag. The effects of an infinite perfect electric conductor plane on a simple antenna can be analytically formulated and explained by image theory and antenna theory [11]. The radiation pattern changes from omnidirectional to directional pattern and the radiation impedance decreases sharply. The total radiation impedance of the original antenna equals the self-impedance Z_{11} minus mutual impedance Z_{12} , since the mirror antenna has equal but opposite current flows according to image theory. When the conductor plate is small (proportional to wavelength), the effect of a metal plate on the antenna parameters was reported by Raunonen et al. [1]. When the distance (h) between the antenna and the plate is within the range of less than 0.01λ (almost closed), the antenna has poor radiation efficiency from 0 to 35%. When $0 < h < \lambda/4$ is fulfilled, the gain will increase with h . And the reading distance r will exceed 2 meters at some distance near $\lambda/4$. Magnetic substrate can be effectively applied to decline the distance h [8, 12]. In order to obtain a small, thin and efficient antenna, μ_r and ε_r of the magnetic substrate can't be too large because large electromagnetic parameters can greatly affect the aperture efficiency. Therefore, μ_r and ε_r of the magnetic substrate can't be too large so as to obtain a small thin and efficient half-wave antenna. As a result, the main challenge for magnetic substrate design is the gain and the impedance matching between the terminal of the tag and that of the integrated circuit (IC).

3. TAG ANTENNA DESIGN AND DISCUSSION

The tag antenna reported in this paper is designed for Alien Higgs-3EPC Generation 2 Class 1 compatible UHF RFID IC from Alien technology with P_{th} of -18 dBm [13]. When the magnetic material

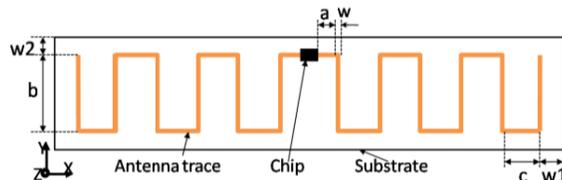


Figure 1. Geometry of the metal tag antenna.

is used as the tag substrate in the metal environment, antenna parameters, such as impedance, radiation pattern, gain and the read range may change. We choose a kind of magnetic substrate (A in the Table 1) which is provided by the National Engineering Research Center of Electromagnetic Radiation Control Materials. The antenna geometry is shown in Fig. 1. In order to be close to the actual experiment, a space of 0.06 mm between our antenna trace and substrate is set. Meandered dipole antenna is a natural choice, considering the size and tunability requirements. The antenna design is modeled and simulated by using the software HFSS. The effect of the geometry of a meander-line antenna on the input impedance was described by G. Marrocco [14], and the effect of parameters (a , b , c , w , w_1 , w_2) were described in detail by S.-L. Chen [2]. The dimensional parameters and a prototype photograph of the magnetic substrate antenna are shown in Fig. 2. The simulated results of the E -field, H -field, and volume loss density of the magnetic substrate of antenna are shown in Fig. 3. It is found that the loss of energy caused by the magnetic substrate occurs in the folding edge of the antenna. The distribution of volume loss density is similar to the magnetic field, but quite different from the electric field, which indicates that the loss depended on the magnetic properties, since $\tan \delta_m (= 0.09)$ is much larger than $\tan \delta (= 0.003)$.

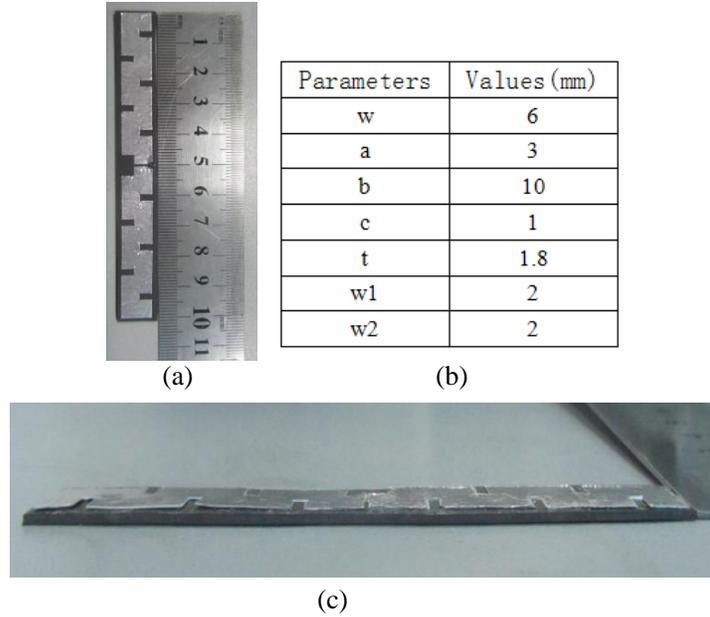


Figure 2. The photograph and physical dimension of the metal tag. (a) The front view. (b) Physical dimension. (c) The side view.

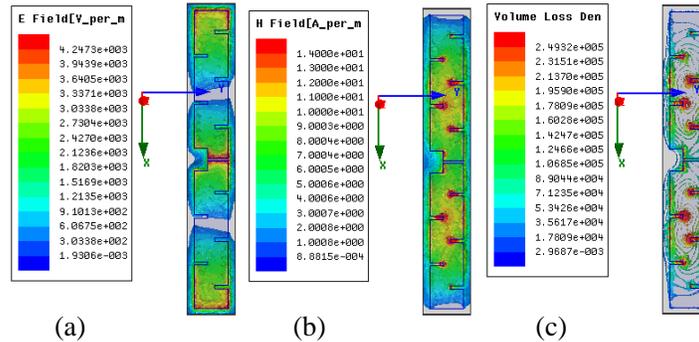


Figure 3. Simulated results of the magnetic substrate tag. (a) E -field. (b) H -field. (c) Volume loss density.

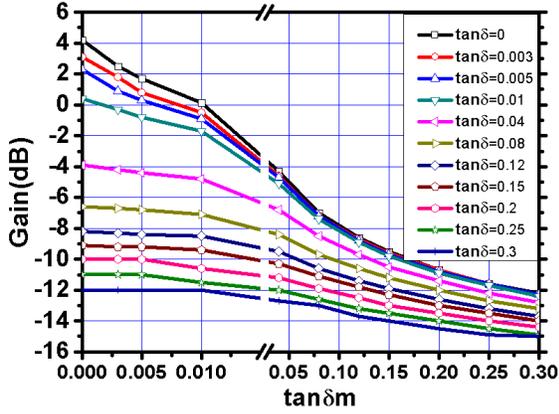


Figure 4. The simulation results gain of different magnetic and dielectric loss tangent.

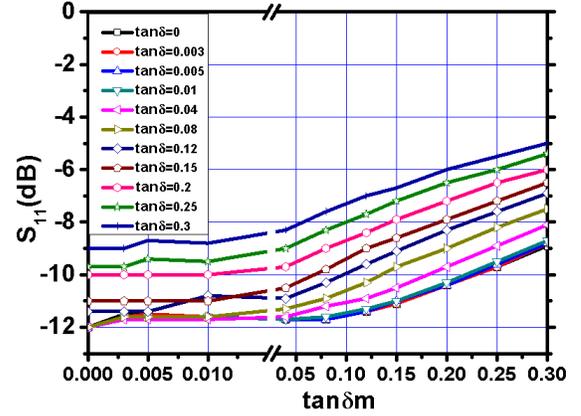


Figure 5. The simulation results S_{11} of different magnetic and dielectric loss tangent.

In order to further verify the behavior of $\tan \delta m$ and $\tan \delta$, S_{11} and gain of the antenna at 922 MHz are simulated with the $\tan \delta m$ or $\tan \delta$ changing from 0 to 0.3 and other parameters unchanged. The simulation results Gain is shown in Fig. 4 and S_{11} is shown in Fig. 5. It is evident from the table that the $\tan \delta m$ and $\tan \delta$ have great impact on the antenna gain. As the dielectric loss tangent or magnetic loss tangent is increased, gain declines rapidly from 4.2 dB to -15 dB, and S_{11} changes from -12 dB to -4 dB. The gain declines rapidly when the $\tan \delta m$ and $\tan \delta$ is increased from 0 to 0.04, but S_{11} changes little at the same time. It is probably due to that S_{11} is related closely to the parameters of antenna trace, while the gain is related closely to the electromagnetic properties of magnetic substrate. Besides, both $\tan \delta m$ and $\tan \delta$ have a similar influence on the gain in spite of different μ_r and ϵ_r , as shown in Fig. 4 and Fig. 5. When the dielectric loss tangent or magnetic loss tangent is less than 0.01, the antenna gain is generally considered to be excellent. However, the gain becomes worse when the dielectric loss tangent or magnetic loss tangent is larger than 0.15.

The relationship between gain and S_{11} is illustrated in Fig. 6, where the maximum reading distance calculated with Equation (1) is presented as a function of the reflection coefficient for various gain of the tag antenna. In Fig. 6, one finds that when the gain of the tag antenna is -14 dB, more than 2 m read range is still achievable. If the gain is improved from -15 dB to 4 dB when S_{11} is lower than -4 dB, the read range will improve more than 15 meters. In the other hand, if S_{11} changes from -12 dB to -4 dB when the gain is less than 0 dB, the maximum reading distance keeps almost the same. Then if the gain of the tag is large enough, good impedance matching is no longer an absolute requirement for achieving one to three meters of read range.

When the $\tan \delta m$ and $\tan \delta$ is increased from 0 to 0.3, S_{11} of the tag changing from -12 dB to -4 dB has little influence on the final reading distance. But when the $\tan \delta m$ and $\tan \delta$ is increased from 0 to 0.3, gain of the tag changing from 4.2 dB to -15 dB leads to the final reading distance dropping more than 15 m. Therefore, when we choose the magnetic material as substrate, the impact on the gain should be considered firstly but not the impedance matching. Besides, since the reading distance depends on the gain and the gain depends on the loss tangent, so the loss tangent leads to lower reading distance. For magnetic materials, the complex permeability represents the relationship between magnetic induction (B) and magnetic field (H). The real part of the complex permeability denotes the energy of magnetic storage, and the imaginary part characterizes the magnetic loss. To obtain appreciable reading distance, both the dielectric loss tangent and the magnetic loss tangent should be less than 0.1 as discussed before. As for the magnetic material, $\tan \delta m$ is normally larger than $\tan \delta$. So we can choose the magnetic materials with $\tan \delta$ less than 0.01 and $\tan \delta m$ less than 0.1. Electromagnetic parameters keep stable around the work frequency.

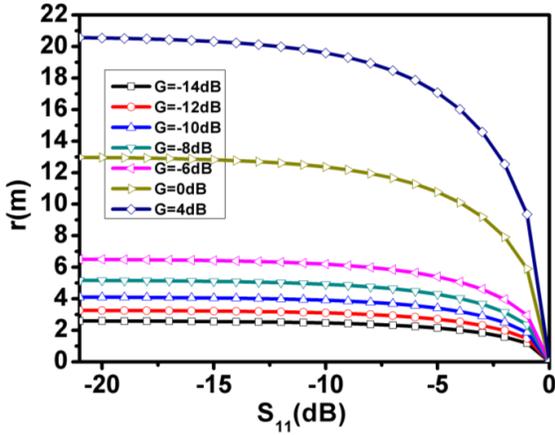


Figure 6. Tag read range as a function of the reflection coefficient at 922 MHz for various values of the tag antenna gain with EIRP = 4 W, $P_{th} = -18$ dBm.

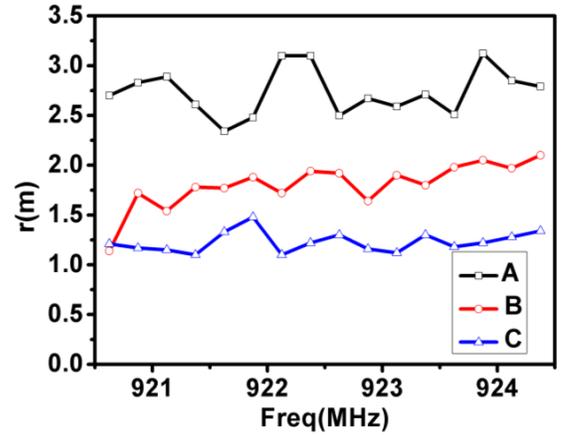


Figure 7. Variations of RFID tag range versus frequency for different substrate.

Table 1. Permeability and permittivity of magnetic substrate at 922 MHz.

material	ϵ_r	$\tan \delta$	μ_r	$\tan \delta m$	thickness
A	6.4	0.003	2.3	0.09	1.8 mm
B	9.8	0.006	4	0.14	1.8 mm
C	10.8	0.007	3.9	0.23	1.8 mm

4. EXPERIMENTAL RESULTS AND DISCUSSION

Practical antenna examples of different magnetic substrate (A, B, C) in this section were executed. The electromagnetic properties of the magnetic substrate were shown in the Table 1. At the working frequency of 922 MHz, the simulation S_{11} of the antenna with magnetic substrate A, B and C, are -12 dB, -8.5 dB and -5.4 dB, respectively, and gains are -7.6 dB, -9.5 dB and -12 dB, respectively. We test the reading range at a normal room with the antenna mounted on metallic plate. The results are shown in Fig. 7. According to Equation (1), the maximum reading distances of the metal tags with substrate A, B and C should be 5.2m, 4m and 2.7m, respectively. Actually, all the test ranges are less than the theoretical values. But the trends are in good agreement: the reading ranges decline with the increase of dielectric and magnetic loss tangent. Because wave of the reading antenna used in the testing is circularly polarized wave and wave of the tag antenna is linearly polarized wave. Antenna will bring energy loss when it receives different types of wave polarization. But the theoretical maximum reading distance calculated with Equation (1) has neglected the polarization matching factor between the reading antenna and the tag.

5. CONCLUSION

Magnetic composite material has been used to design the metallic RFID tag. The influences of electromagnetic properties of magnetic substrate, especially the electromagnetic loss, on the gain of the tag antennas were studied. Both simulations and experiments indicate that the increase of electromagnetic loss is the main reason of gain decrease. To obtain good reading distance, both the dielectric loss tangent and the magnetic loss tangent are at least less than 0.1. The conclusion offers meaningful guidance for future studies of magnetic substrate metal tag antenna.

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