An RFID Tag Capable of Free-Space and On-Metal Operation

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***Abstract*— The majority of commercial UHF RFID tags are based on the dipole antenna, and it is well known that tag performance degrades significantly when the tag is placed near a conducting surface. Here, we present a new antenna that operates as a dipole when in free space, but when placed on a conducting surface, it operates as a relatively efficient microstrip antenna. The antenna is shown to have near-optimal free-space performance and yield a peak gain of approximately 6 dBi of effective gain on a copper surface.**

***Index Terms*— Dipole antenna, microstrip antenna, passive UHF RFID tags, RFID.**

I. Introduction

Several independent researchers have verified a classic problem: the performance of passive UHF RFID tags degrade when placed near a metal surface [1]–[4]. This is an unfortunate situation, since industry continues to seek a low-cost way to tag metal assets. Microstrip-based antennas modified for operation with RFID ICs (e.g., [5]–[8]) offer a useful alternative, but are considerably more expensive to fabricate. Often, industry simply provides a thin (e.g., 3 to 6 mm) low dielectric material such as a flexible foam in order to provide enough separation from the metal surface to provide adequate, though severely degraded, performance. A foam separation of 3.2 mm can yield a performance degradation of 16 dB or more over free-space performance, resulting in a reduction in read distance of about 85% [4].

Here, we present a type of dipole / microstrip antenna with classical features and a 3.18 mm low dielectric material. The tag is designed so that it presents both a near-optimal impedance match when operating as a dipole (in free space) and an excellent ($\approx$ 6 dBi) performance when operating as a microstrip (on a flat metal surface).

II. Background

A passive UHF RFID system [9] consists of a transponder, also called a tag, and an interrogator, also called a reader. The reader provides power via RF energy, commands via a protocol (e.g., [10]), and timing. The tag consists of an IC and an antenna. The tag communicates by modulating the IC impedance, which changes the scattering characteristics of the antenna, which can be detected by the reader.

For an RFID tag to operate, the IC must receive sufficient power to run the circuitry and provide enough backscatter signal strength for the reader to detect the response. For many systems, we can assume that the system is limited in the forward channel (reader to tag), and if the tag responds, then the reader will detect the response. This is not always the case, but it is a good working assumption.

The majority of passive UHF RFID tags are manufactured using a high-speed, low-cost, roll-to-roll process. Introducing a low-cost, thin foam dielectric spacer such as high density polyethylene is attractive because it introduces little additional cost and is easily integrated into the roll-to-roll process. In fact, many converters are able to produce these "foam attached tags," or FAT tags, with minimal change to existing equipment. The commercial interest in these tags are based on a combination of low additional material cost and the ability to easily integrate to existing manufacturing equipment and processes, which results in a low-cost product.

As with many antennas, the bandwidth of an RFID tag is typically limited by the impedance of the antenna. The reactive IC impedance can further aggrivate this problem. Commercial RFID use a printed (or "ribbon," or "flat") dipole because of the low manufacturing cost involved. Further, they are commonly limited to about 92 mm in length in order to fit comfortably on a 101.6 mm wide label. At 915 MHz, a half-wave resonant dipole is approximately 160 mm long, so the antenna is electrically short, and commonly narrow, causing the antenna to have a large quality factor Q (nominally 15) and thus be relatively sensitive to the environment. In this paper, we consider operation within the UHF ISM band in North America that ranges between 900 and 930 MHz.

The impedance of a dipole antenna near the fundamental resonant mode is approximately that of a series RLC circuit. It is well-known that placing a dipole above a ground plane significantly decreases the radiating resistance, reduces the resonant frequency, and dramatically increases the Q of the antenna [11]. Typically, the dipole antenna consists of two elements that are fed differentially, but a microstrip consists of a single conducting element and is fed at a single location with respect to ground. Common microstrip feeds include a probe, direct contact along one of the edges, or some other form of coupling. The impedance of a microstrip antenna at resonance behaves more like that of a parallel RLC circuit.

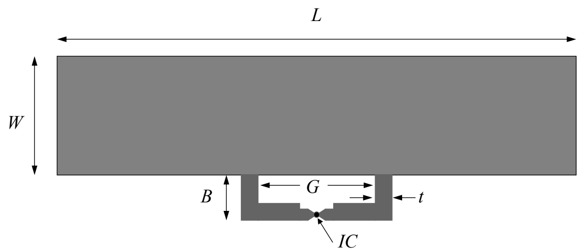

Fig. 1. Proposed RFID tag geometry. Here, *L*=142 mm, *W*=30 mm, *G*=16 mm, *B*=12 mm, and *t*=5 mm.

The T-match [12] is used to modify the impedance of a dipole antenna, and is commonly use RFID tags [13]. The T-match is normally used to decrease the resistance and to increase the reactance to provide a conjugate impedance to the IC impedance. However, the same structure may also be used to feed an identical microstrip antenna [14]. The interesting question is whether one is able to use a T-match to effectively modify a dipole impedance and simultaneously to feed and provide an impedance match for a microstrip antenna. I.e., can a single antenna using a T-match be both a dipole and a microstrip antenna? If so, one could develop FAT tags that perform well in free space and when attached to metal assets.

III. Proposed Antenna

The proposed tag antenna shown in Figure 1 is a flat dipole that uses a T-match matching circuit. The design IC impedance $Z_c = 12 - j133$ Ohms. Permanently attached to one side of the antenna is a 3.18 mm HDPE foam ($\epsilon_r = 1.09$ and $\tan\delta = 0.001$). The antenna, IC, and foam substrate comprise the proposed tag. When the tag is in free space, the tag operates as a "normal" dipole-based tag. However, when the dielectric is placed on a ground plane, the tag behaves as a microstrip antenna. The substrate may include a pressure-sensitive adhesive to attach it to (potentially metal) objects.

When operating as a microstrip antenna, the feed behaves like a classic edge-feed and the T section behaves like simple transmission lines. The relatively short transmission lines primarily add inductance to the feed impedance. Unlike a classic edge-fed antenna, the proposed structure uses two symmetric feeds to achieve a balanced feed structure.

To design the antenna, we arbitrarily start with *W* equal to 30 mm. Next, the parameter *L* is chosen so that the antenna, as a microstrip, has a resonant frequency of approximately 945 MHz, so the antenna, as a microstrip, is designed to operate below resonance where the resistance is smaller and the reactance is a modestly inductive. The remaining parameters *G*, *B*, and *t* are varied until a suitable tradeoff between the dipole and microstrip impedance is achieved. We note that the proposed antenna is too large for many practical applications; however, the same methodology can be applied to a more compact geometry if desired.

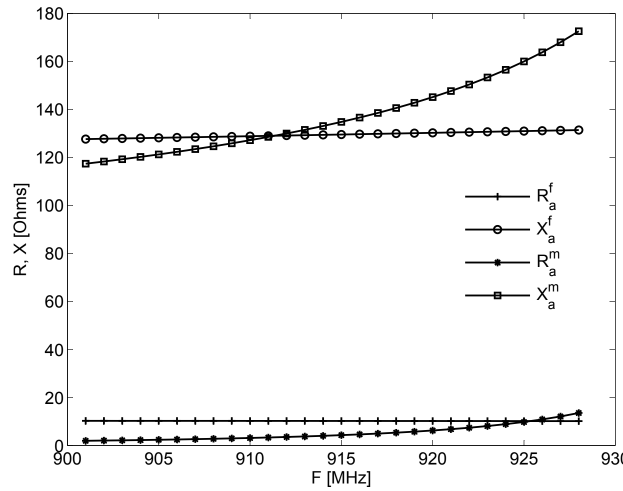

Fig. 2. Simulated impedance of antenna as a dipole and microstrip.

Figure 2 shows the simulated resistance R and reactance X of the antenna when in free space ($Z_a^f = R_a^f + jX_a^f$) behaving as a dipole, and when on metal ($Z_a^m = R_a^m + jX_a^m$) behaving as a microstrip. The wide, long dipole has a very low Q, as expected, and thus we see almost no change in impedance over the band. As a microstrip, we see a significant increase in resistance and reactance at the higher ferquencies as the antenna approaches resonance. Clearly, Z_a^m achieves a less-than-optimal impedance match; power transfer efficiency is being traded for bandwidth.

We can define the power transfer efficiency between the tag and IC as [15]

$$\tau = \frac{4R_a R_c}{|Z_a + Z_c|^2},$$

where the subscripts a and c denote the antenna and chip resistance or reactance, respectively. Figure 3 shows how τ^f and τ^m change with frequency. We can see a near-optimal match as dipole, and as a microstrip, we see the power transfer efficiency range between -1 and -6 dB loss over the band.

Next, we experimentally evaluate the tag performance. Based on simulated results of the antenna efficiency η and directivity D, we can predict the *effective gain*, which we define as $G_{\text{eff}} = \eta\tau D$.

To validate the results, we performed a simple experiment. The proposed tag, shown in Figure 4, is placed two meters from an instrumented RFID reader in a partially anechoic environment. The transmitting antenna uses a linearly polarized patch antenna with a gain of 6 dBi. The reader is programmed to operate at a fixed frequency and power setting. At each frequency, the power setting is varied until we find the lowest power setting in which the

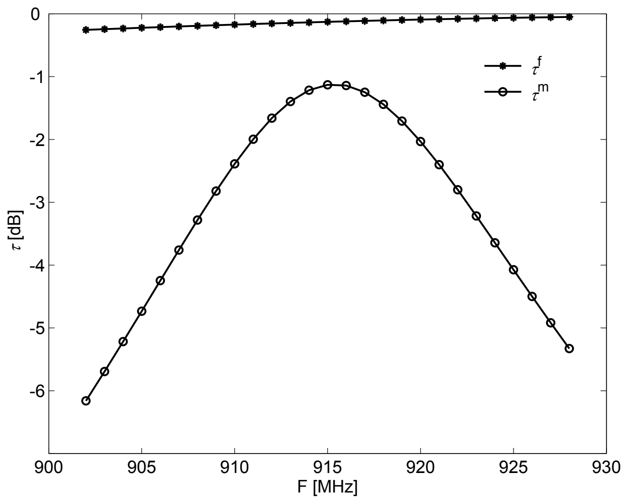

Fig. 3. Power transfer efficiency vs. frequency of proposed antenna as a dipole and microstrip calculated from simulated antenna impedance.

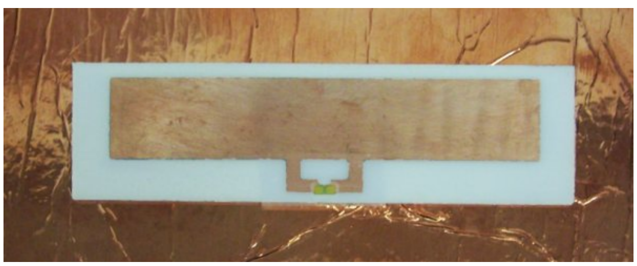

Fig. 4. Picture of the proposed RFID tag mounted on copper plane.

reader is able to successfully read the tag in at least 50% of the read attempts. Generally, the power delivered to the IC, using the notation of [16], is expressed as:

$$P_r = \frac{P_t G_t G_r}{(4\pi\lambda)^2 d^2}\tau\rho\,.$$

(We use this notation only within this paragraph.) Here, P_t is the transmitted power, G_t is the gain of the transmit antenna (6 dBi), G_r is the gain of the receive (tag) antenna, $\lambda = c/f$ is the free space wavelength (≈ 0.327 m), d is the distance separating the two antennas (2 m), and ρ is the polarization match. Since both antennas are linearly polarized and aligned, we assume $\rho = 1$.

Note that the simulated $D^f = 3.4$ dBi. We observe a minimum turn-on power of the tag in free space of 15.9 dBm, and assuming $\tau^f = \rho = \eta = 1$, we calculate the minimum turn-on power of the IC to be -12.4 dBm. Using that, we can estimate G^m_{eff}. Admittedly, this is an imperfect metric and has potential problems, for example, if the IC impedance is different than anticipated, or the simulated and actual antenna impedance differ. However, the results do show consistent agreement with simulation, so we have

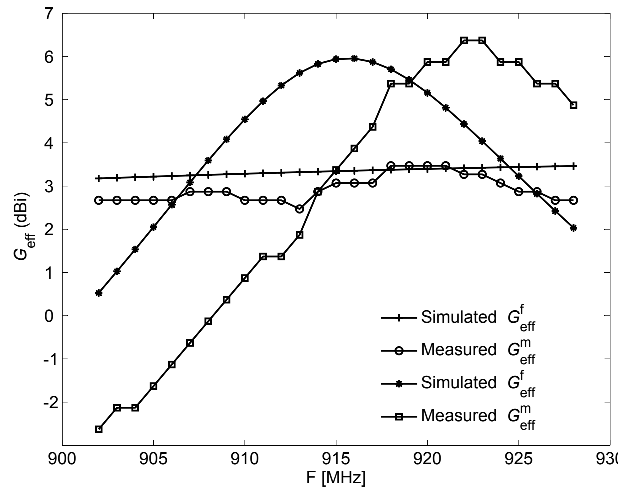

Fig. 5. Effective gain of proposed antenna as a dipole and microstrip.

some reason to trust the results.

We compare the predicted (via simulation) and measured (via minimum reader turn-on power) effective gain of the proposed antenna in Figure 5. Here, we see good consistency with the free-space measurement and a flat G^f_{eff} with respect to frequency. More interesting is the performance of the tag as a microstrip. Again, we see excellent agreement with prediction, except there is a difference in frequency of peak performance by about 9 MHz, or 1%. This is likely due to the dielectric constant of the foam that we now estimate is 1.098 instead of the previously assumed 1.09. A revised length of 143.4 mm would be recommended to center the peak gain of the antenna behaving as a microstrip.

Note that the peak $G^m_{\text{eff}} > G^f_{\text{eff}}$ primarily because $D^m > D^f$, but the bandwidth of the tag on metal is substantially less. At the edge of the band, the tag suffers from a considerable reduction in G_{eff}, but is still good relative to that of a dipole.

IV. Conclusions

We propose an antenna that illustrates the viability of constructing an RFID tag with a thin foam backing material that is capable of operating efficiently both as a dipole antenna (in free space) and as a microstrip antenna (attached to metal). The antenna yields near-perfect free-space performance and a peak on-metal performance of approximately 6 dBi. The antenna uses a classical T-match to a dipole, which, when attached to metal, operates as a microstrip antenna with balanced edge feeds. We operate the microstrip below its self resonance, where the resistance is low, reducing the peak performance by 1 dB to achieve improved bandwidth.

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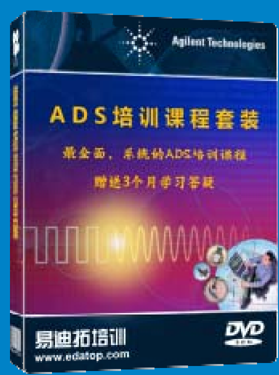

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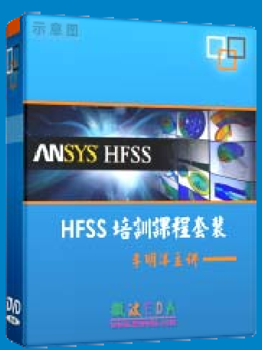

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