Effects of Antenna Material on the Performance of UHF RFID Tags

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***Abstract*— The RFID industry is growing rapidly, especially in the UHF frequency band that is being used extensively in supply chain management. Traditionally, inlays have been constructed from etched copper or aluminum. Etching is a subtractive process that uses chemicals and can creates waste. Recently, inlays are manufactured using silver-based inks. Printing is an additive process, so it has a number of advantages. However, silver inks suffer from two important drawbacks: relatively poor conductivity and environmental concerns. Those concerns have spurred developments in other additive technologies, such as vapor-deposited aluminum, electroplated, and electro-less deposited copper. This paper quantizes by measurement the performance of antennas with three materials, four line widths, and various thicknesses, which may serve as guidelines about how to design antennas with the various materials.**

I. INTRODUCTION

RFID, and especially passive UHF RFID based on the ISO 18000-6c protocol, has made its way into high-volume usage, especially around logistics and supply chain management (e.g., [1]). One retailer is expected to receive over 150 million RFID tags in 2006, with that number increasing exponentially for the next few years. Thus, the cost of the RFID tag is a key concern, since RFID tags have a limited lifespan. Recently advertised prices (as of November 2006) show volume pricing under $0.10 US, with prices expected to continue to fall. Thus, every component of an RFID tag is under constant scrutiny for the slightest cost savings.

One area of current activity is the utilization of different materials and processes for manufacturing antennas. Traditionally, antennas are manufactured using thin metallic foil (copper and aluminum are common) adhered to a thin PET substrate (2-3 mils or 50-75 microns are typical). The metal is then etched using a photolithographic process. This process is a “subtractive” process, as metal is removed in order to form the antenna. This process is generally considered wasteful, since it requires large amounts of chemicals and energy and produce waste material, even if portions are recyclable.

Recently, new processes have been proposed based on conductive inks. The inks are deposited using traditional printing processes and then cured. While the inks are more expensive, the process of using inks is purely an additive one. Thus, the costs of tags using conductive inks can be competitive with, even less expensive than, that of subtractive processes. These inks are generally based on silver, and while pure silver is highly conductive, these inks are known to have relatively poor conductivity (according to our measurements, less than 10% the conductivity of silver). Another significant concern involves disposal of silver-based inks, since there are possible health concerns, and thus some governments limit their use. Even so, it has been found that the silver inks provide adequate, if not excellent performance for RFID tags [2]. However, the parameters under which the materials are adequate and accurate measurement of antenna efficiency of the materials have not yet been systematically reported.

Concurrently, there has been activity in processes in which highly-conductive copper can be deposited onto a PET substrate. One process involves printing a thin, conductive layer (perhaps using silver inks) and then electroplates copper onto the conductive substrate. A newer process involves printing a catalytic ink on the substrate followed by immersion in a solution that results in the chemical (electro-less) deposition of copper. Copper additive processes potentially have the best aspects: an additive process that minimizes waste, avoids controversial metals, and results in a highly-conductive antenna utilizing the minimal amount of metalic material.

In this paper, we evaluate the competing technologies for UHF RFID tag antennas, namely etched copper, deposited copper, etched aluminum, and two brands of silver ink. We give extensive evaluation of the efficiency of dipoles of different thicknesses and widths, using analytical models, simulation models, and direct measurement. We validate these models by constructing RFID tags.

II. APPROACH

The goal of this effort was to determine the relative worthiness of competing technologies for UHF RFID antennas. A three step process was taken to meet the goals of this project. They were:

1) Develop a simple analytic model for the efficiency of dipole antennas with various material conductivities, widths and thicknesses.
2) Measure the input resistances of various dipole samples with a network analyzer using a balun circuit board and compare them with models created in a moment-method (MOM) simulation package (Ansoft Designer [3]).
3) Validate the models and performance measurements with the performance of impedance matched RFID tags.

We describe each of these steps below.

A. Analytic Model

The efficiency of a radiating antenna is defined as the ratio of the power delivered to the radiation resistance R_r to the

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power delivered to radiation resistance R_r and loss resistance R_l [4]. Thus, the radiation efficiency can be written as

$$\eta = \left(\frac{R_r}{R_r + R_l} \right) \tag{1}$$

The radiation resistance R_r is a function of the antenna type and dimensions, but is generally independent of the ohmic losses in the antenna itself. Hence, R_r can usually be obtained from analytical or numerical modeling techniques under the assumption that the antenna elements are lossless.

The calculation of the loss resistance R_r of an antenna in terms of its material properties is, in general, a more difficult problem for most antennas, but is relatively simple for metal dipole antennas, since the shape of the current distribution on a dipole is not significantly affected by ohmic loss.

A simple expression for the input loss resistance of a dipole can be derived in terms of the well-known expression for the current distribution on a dipole antenna [4]:

$$I(z) = I_m \sin \left[k \left(\frac{l}{2} - |z| \right) \right] , \tag{2}$$

where I_m is the maximum current on the dipole, l is the total length of the dipole, $k = 2\pi/\lambda$ is the wave number of free space, and position $z = 0$ is the center of the dipole. At resonance, $I_m \approx I(0)$. This implies a sinusoidal current distribution with nulls at the end points. The power lost at any position z within width dz on the dipole is

$$dP = \frac{1}{2} I_m^2 \sin^2 \left[k \left(\frac{l}{2} - |z| \right) dR \right] , \tag{3}$$

where dR is the resistance of the section. If the thickness of the dipole is on the order of a skin depth (s) or less, the current can be approximated to flow uniformly throughout the dipole cross section, so dR is simply given by

$$dR = \frac{dz}{\sigma a} , \tag{4}$$

where σ is the DC conductivity of the metal, and a is the effective cross sectional area of the dipole. If $t < 2s$, then $a = wt$, else $a = 2ws$, where w and t are the width and thickness of the dipole respectively. Substituting (4) into (3) and integrating over the length of the dipole, the dissipation power is found to be

$$P_{loss} = I_m^2 \frac{1}{\sigma a k} \left[\frac{kl}{4} - \frac{1}{4} \sin kl \right] . \tag{5}$$

In addition, the dissipated power is related to the input (feed) current $I(0)$ by

$$P_{loss} = \frac{1}{2} I(0)^2 R_l , \tag{6}$$

where R_l is the antenna input resistance due to material losses. Substituting (5) into (6) yields:

$$R_{loss} = \frac{2}{\sin^2 kl/2} \cdot \frac{1}{\sigma a k} \left[\frac{kl}{4} - \frac{1}{4} \sin kl \right] . \tag{7}$$

Further, for the specific case of half-wave dipoles, where $l = \lambda/2$, we obtain

$$R_{loss} = \begin{cases} \frac{\lambda}{4\sigma w t} & t \leq 2s, \\ \frac{\lambda}{8\sigma w s} & t > 2s. \end{cases} \tag{8}$$

This analytical expression for the loss resistance of a half wavelength stripline (i.e., wide but thin) dipole commonly used in RFID tags. The expression takes into account conductivity, wavelength and stripline dimensions. The top expression can be used for cases when the thickness of the dipole is up to twice the skin depth of the material at the frequency under consideration. When the thickness is much greater than two skin depths, we can make the approximation that the current flow is only in the skin of the material. These approximations are known to hold when the thickness is less than the skin depth or much greater than the skin depth, the maximum error being when the thickness is close to two skin depths. Our results show that the analytic expression is accurate even in cases when the thickness is close to twice the skin depth.

B. *Direct Measurement of Antenna Efficiency*

To validate the analytic model, printed antennas of various thicknesses, widths and materials were constructed on a 4 mil thick PET substrate, samples of which are shown in Figure 1. A feed board consisting of a balun and balanced output terminals, shown in Figure 2, was constructed so that these antennas could be easily attached to the balanced terminals and driven with a coaxial cable. A Mini-Circuits TC1-10 balun was used for this purpose, because it was compact and has good behavior between 680 to 1050 MHz [5].

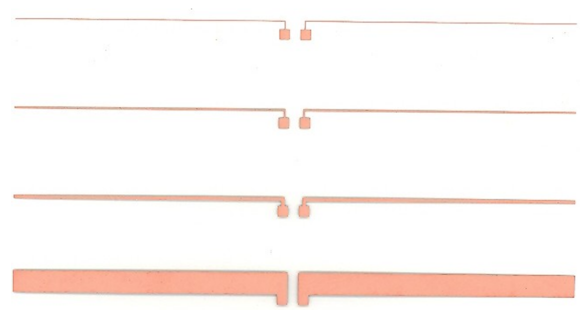

Fig. 1. Dipoles of varying line widths: 0.25, 0.5, 1, and 6.35 mm.

Fig. 2. Image of the circuit board with balun used to measure dipoles.

After calibrating the network analyzer with the balun board, the network analyzer performed a frequency sweep

TABLE I

CONDUCTIVITY AND SKIN DEPTH OF MATERIALS USED FOR DIPOLE SAMPLES.

Material	Conductivity $(S/m) \times 10^6$	Skin Depth (μm) at 915 MHz
Bulk copper (BC)	58	2.18
Deposited copper (DC)	50	2.35
Bulk silver	61.8	2.1
Bulk aluminum	36	2.8
Silver ink A	5.1	7.31
Silver ink B	4.2	8.11

TABLE II

CONDUCTIVITY AND SKIN DEPTH OF MATERIALS USED FOR DIPOLE SAMPLES.

Material	Thickness (μm)
Deposited copper (DC)	1.2, 1.4, 2.4, 3.2, 3.5, 4.1
Bulk copper (BC)	18
Bulk Aluminum (BA)	10.2
Silver ink A	7, 9
Silver ink B	4, 6

over a range that included the resonant frequency. The dipole input impedance was monitored as the frequency of the network analyzer was swept through the antennas resonance range. The input resistance at each antennas resonant frequency (where the input reactance was zero) was then recorded.

Sample dipoles were made of the following materials: bulk copper that had been etched, electro-less deposited copper, bulk aluminum that has been etched, and two types of commercially available silver inks from different vendors. The conductivities of the bulk copper, bulk silver, deposited copper, and silver inks were measured by their DC resistance, length, and cross-sectional area. The measured conductivities, along with the calculated skin depths, are shown in Table I. Note that the bulk aluminum conductivity is slightly less than that of published values of pure Al, perhaps because the aluminum was an alloy.

Dipoles of line widths 0.25, 0.5, 1, and 6.35 mm were constructed for each material and with varying thickness. The combination of materials and thicknesses of tested dipoles are indicated in Table II. The lengths of all the dipoles were kept constant at 160 mm so as to enable a comparison of efficiency of dipoles made of different materials, thicknesses, and line widths.

Since the input radiation resistance of a dipole is largely independent of the dielectric loss of the substrate, we were able to determine the input resistance by using a commercial moment method code, which is capable of determining input impedances of thin dipoles with high accuracy. These radiation input resistances were then subtracted from the measured input resistances to determine the input loss resistances. These calculated radiation resistances were then subtracted from the measured input resistances to obtain the input loss resistances, and the dipole efficiencies were calculated via Equation (1).

TABLE III

RADIATING RESISTANCE OF DIPOLES WITH VARYING WIDTH.

Width (mm)	f_0 (MHz)	$R_r(\Omega)$
0.25	898	54.64
0.5	909	56.29
1	918	57.27
6.35	903	67.73

The measured efficiencies were then compared with the efficiency calculated using the analytic model for loss resistance (i.e., Equation (2)). Finally, efficiencies were also calculated from the estimates of the loss resistances determined numerically from the moment method code.

C. Validation with RFID Tags

While the dipole efficiency measurements are be shown to be accurate, it is also helpful to validate those measurements using actual RFID tags. To that end, RFID tags matched to the published impedance specifications of RFID ICs at 915 MHz were developed. Each of them had the same RFID chip attached (using a removable "strap") to eliminate any bias due to different chips. The tags were placed a fixed distance from the reader antenna (2 meters), and the power output of the reader was adjusted to be as low as possible and still read the tags. (The reader power settings were validated through direct measurement.) Then the turn-on power of the RFID tags was measured in a canonical setup using the same RFID tag reader in each case. RFID tags were of 1 mm line width copper from the same materials as the dipoles.

Fig. 3. Image of the RFID tag matched to the chip impedance.

III. EXPERIMENTAL RESULTS

Based on the approach described in the previous section, results from analytic expression, direct measurement of antenna efficiency, simulations and validation with RFID tags are presented in three parts.

A. Predictions and Measurements of Copper Dipoles

The input resistance at resonance for each dipole was measured using a network analyzer. This measured value is the sum of R_r and R_l, and knowing R_r from Table III, the efficiency can be evaluated. We compare this value with the efficiency calculated from Equation (8) and with the efficiency obtained from simulation of dipole models in the method of moment (MOM) code. The efficiency obtained from our analytical model (η_a), simulation (η_s), and direct measurement (η_m) is summarized in Table IV. Note that there was a small discrepancy between the simulated and measured resonant frequency, so we used the measured resonant frequency for computing η_a.

TABLE IV

EFFICIENCY OF COPPER DIPOLES.

W (mm)	Cu type	t (μm)	η_a	η_s	η_m
	DC	1.2	90.68	91.20	89.27
	DC	1.4	91.90	92.25	89.71
	DC	2.4	95.11	94.61	92.28
0.25	DC	3.2	96.29	95.46	93.34
	DC	3.5	96.59	95.44	93.74
	DC	4.1	97.08	95.34	94.24
	BC	18	97.62	95.03	94.93
	DC	1.2	95.32	95.37	90.54
	DC	1.4	95.96	96.40	93.44
	DC	2.4	97.61	97.66	94.48
0.5	DC	3.2	98.19	97.84	96.65
	DC	3.5	98.35	97.84	96.83
	DC	4.1	98.58	97.78	96.70
	BC	18	98.85	97.61	96.80
	DC	1.2	97.67	94.40	92.46
	DC	1.4	98.00	94.68	93.46
	DC	2.4	98.82	95.71	94.09
1	DC	3.2	99.11	95.87	95.26
	DC	3.5	99.19	95.95	95.34
	DC	4.1	99.31	95.75	95.29
	BC	18	99.44	95.67	95.43
	DC	1.2	99.68	99.62	98.34
	DC	1.4	99.72	100	98.44
	DC	2.4	99.84	100	99.40
6.35	DC	3.2	99.88	99.78	99.50
	DC	3.5	99.89	99.78	99.40
	DC	4.1	99.91	99.76	98.57
	BC	18	99.92	99.96	98.92

The data in Table IV are plotted in Figures 4–7. Note that the bulk copper (etched) dipoles are 18 microns appear on the same graph as the deposited copper dipoles.

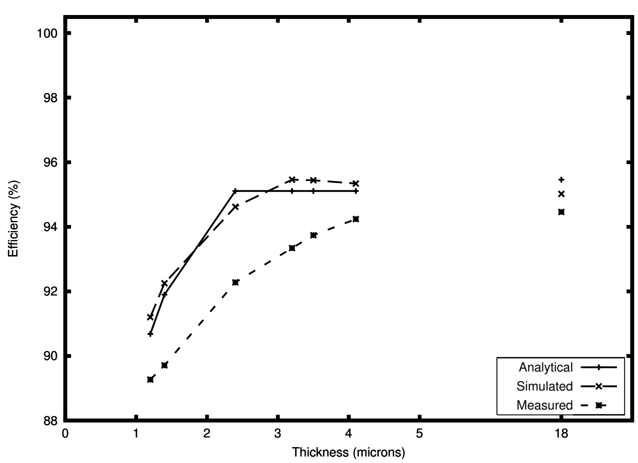

Fig. 4. Efficiency of 0.25 mm wide copper dipoles.

B. Predictions and Measurements of Silver Ink Dipoles

A similar data set was obtained for silver ink dipoles. Recall that the conductivity of silver inks was less than one tenth that of copper. The conductivity of silver inks was found to be fairly consistent among samples. The length of all silver ink dipoles was also 160 mm, the line widths were 0.25, 0.5, 1, and 6.25 mm, and the thicknesses were approximately 4, 6, 7, and 9 μm.

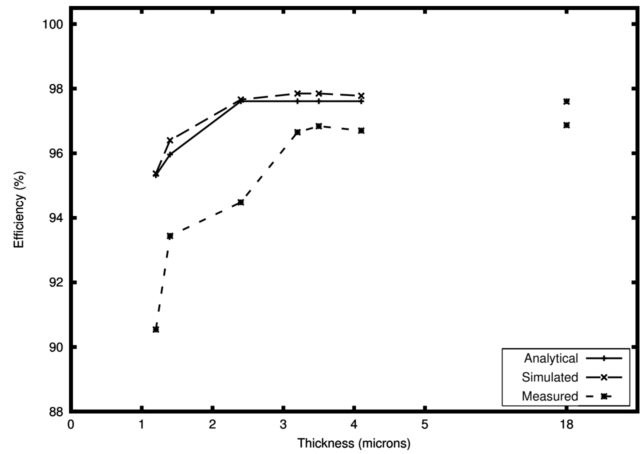

Fig. 5. Efficiency of 0.5 mm wide copper dipoles.

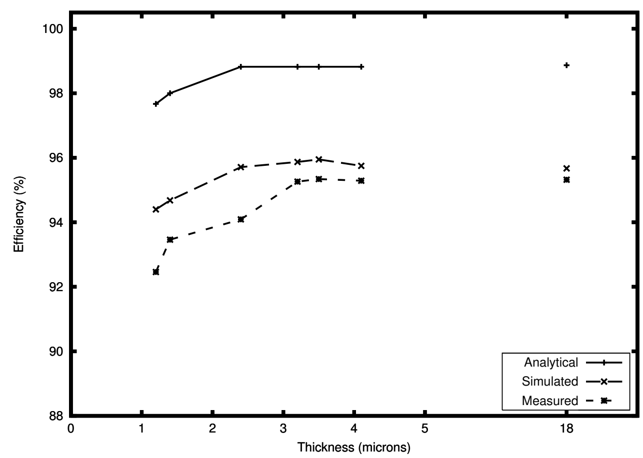

Fig. 6. Efficiency of 1 mm wide copper dipoles.

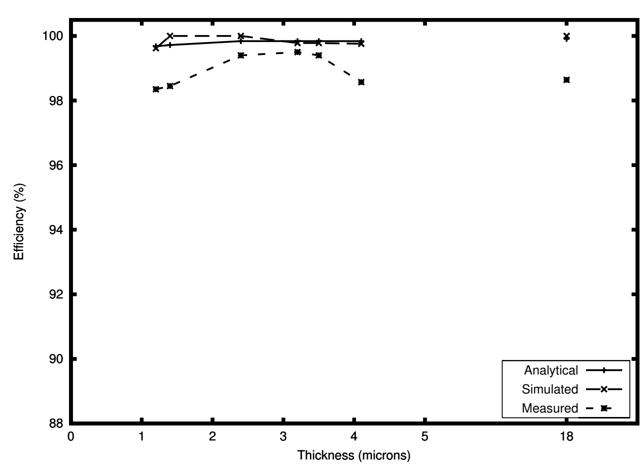

Fig. 7. Efficiency of 6.35 mm wide copper dipoles.

TABLE V
EFFICIENCY OF SILVER INK DIPOLES.

W (mm)	Ag type	t (μm)	η_a	η_s	η_m
0.25	A	4	76.90	74.87	75.74
	A	6	83.32	81.86	80.21
	B	7	82.75	83.66	80.88
	B	9	86.05	85.86	82.65
0.5	A	4	87.35	85.59	82.01
	A	6	91.20	90.15	85.22
	B	7	90.87	91.14	88.13
	B	9	92.75	92.61	89.12
1	A	4	93.41	89.29	87.96
	A	6	95.51	91.69	89.26
	B	7	95.33	92.19	90.35
	B	9	96.33	92.70	92.19
6.35	A	4	99.06	98.69	96.39
	A	6	99.37	99.06	97.99
	B	7	99.35	99.59	98.00
	B	9	99.49	99.68	98.30

TABLE VI
EFFICIENCY OF ALUMINUM DIPOLES.

W (mm)	t (μm)	η_a	η_s	η_m
0.25	10.2	97.03	95.81	93.21
0.5	10.2	98.55	99.07	98.48
1	10.2	99.29	96.76	95.66
6.35	10.2	99.90	100	99.24

Table V shows the efficiency found using the analytic model, the simulated data and from measured data.

The graphs for efficiency for various silver ink dipoles are as shown in Figures 8–11. Note the change in scale on the Y-axis between Figures 4–7 and 8–11.

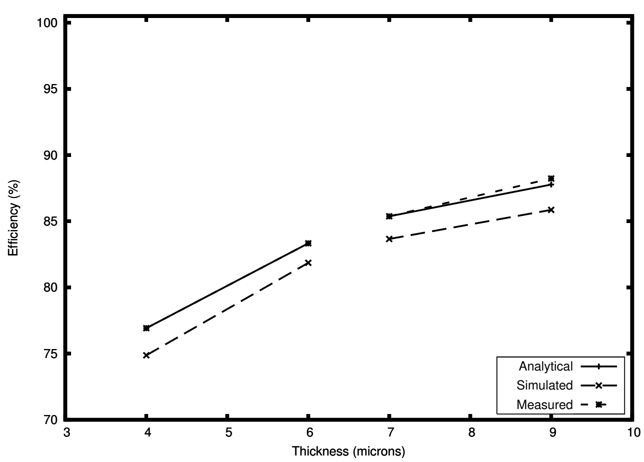

Fig. 8. Efficiency of 0.25 mm wide silver dipoles.

C. *Predictions and Measurements of Aluminum Dipoles*

Table VI shows the analytical, simulated, and measured efficiency of aluminum dipoles antennas.

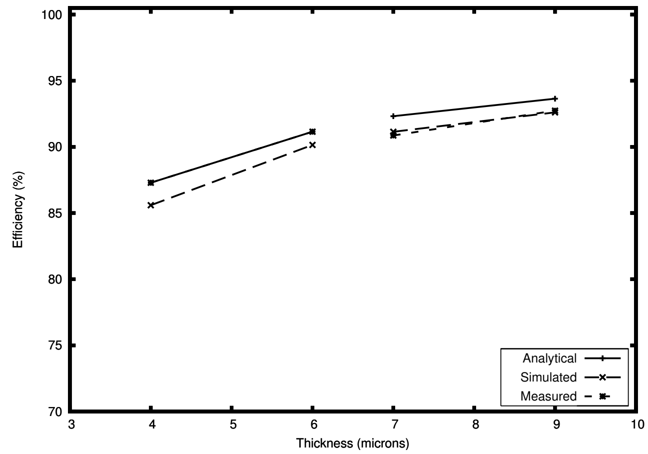

Fig. 9. Efficiency of 0.5 mm wide silver dipoles.

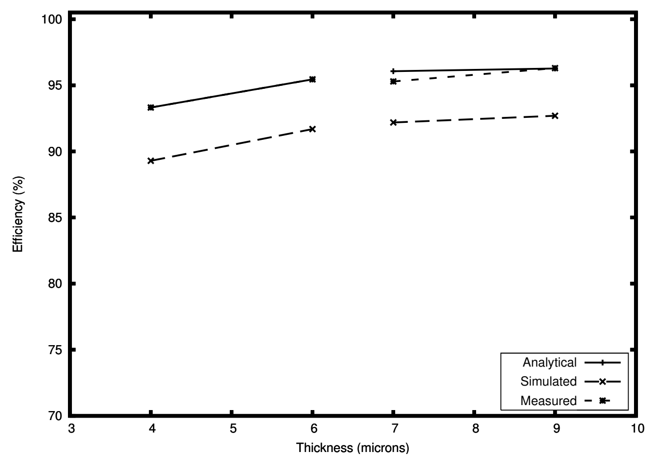

Fig. 10. Efficiency of 1 mm wide silver dipoles.

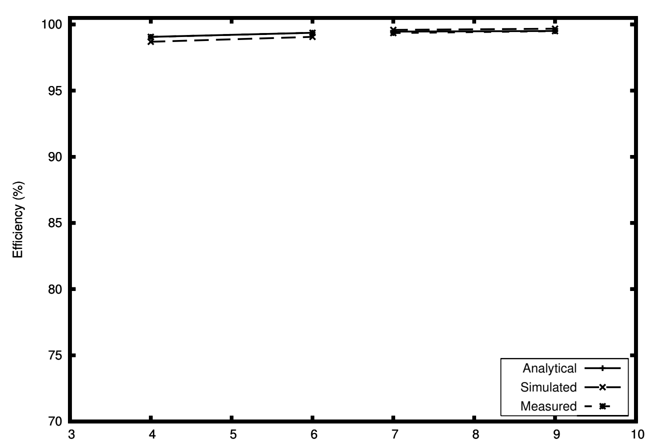

Fig. 11. Efficiency of 6.35 mm wide silver dipoles.

TABLE VII
TURN-ON POWERS OF VARIOUS RFID TAGS.

Material	Thickness (μm)	Width (mm)	Turn-on power (dBm)
Copper BC	18	1	20.5
Copper DC	2	1	20.5
Silver ink A	6.5	1	21.5
Silver ink B	6.5	1	21.5

D. Validation with RFID Tags Using Copper and Silver Ink Tags

Using the test set-up described above, we tested the turn-on power of various tags using an RFID tag reader. The reader was able to adjust the power output in 0.5 dBm increments. The turn-on power measured for different RFID tags is show in Table VII.

IV. INTERPRETING THE RESULTS

A. Measurement of Antenna Efficiency

It can be observed from the plots that the analytical formula developed to predict the loss resistance of a dipole, i.e. Equation (8), gives values which are close to those simulated measured values, provided the thickness of the samples under consideration is up to a few skin depths.

Note that the 1 mm wide dipole antennas made of copper and aluminum were generally simulated and measured to be more efficient than 0.5 mm dipole antennas. This is likely due to small differences in the feed structure of the dipole antenna that is accurately simulated but not accounted for in the analytical model.

Copper dipoles were found to be more efficient than silver ink dipoles of similar dimensions due to the higher conductivity of copper inks. It was found that a thickness of 2 microns copper would be sufficient to make a highly efficient deposited copper dipole, but to make a silver ink dipole which shows a similar efficiency it is needed to have thickness of about 8 microns. (Note that these are both about one skin depth.)

The resonant frequency of dipoles of the same thickness but different widths showed some variation, which is due to the slight differences in antenna geometry.

B. Validation with RFID Tags

Observing the turn-on power of the RFID antennas shows little difference in any of the results, as expected. We expect approximately 95% efficiency for the 18 μm bulk copper tag, 94% efficiency for the 2 μm deposited copper tag, 93% efficiency for the silver A tag, and 95% efficiency for the silver B tag. None of these differences are significant enough to measure with 0.5 dB accuracy.

We do see a very good agreement between the two copper tags and the two silver tags. The difference between copper and silver is larger than expected (we expected to see no measurable difference) and attribute it to either measurement error, or a slightly poorer impedance match that could be eliminated with a more finely-tuned design.

V. CONCLUSION

The simple analytical model showed good agreement with an MOM simulation package and measured results.

We found that various silver inks performed well regardless of conductivity less than 1/10th that of copper. The thicker application yielded antennas that were consistently 80 to 99% efficient. This result agrees with the findings of [2] in that silver inks are suitable for UHF RFID antennas. The aluminum antennas were quite competitive with copper, although they require more thickness to achieve the same level of performance.

We also found that deposited copper was highly conductive, about 86% that of bulk copper. This superior conductivity allows copper antennas to be considerably thinner. Our results show that for the thin deposited copper with narrow line widths (0.25 and 0.5 mm), that the thinner copper was always superior to thicker silver ink. However, wider dipoles (1 and 6.35 mm) with the thicker silver were measured to be comparable and in some cases more efficient than thinner, deposited copper. At the same thickness (4 m), the 1 mm wide deposited dipoles were still measurably more efficient than silver, though at 6.35 mm widths, the differences were within experimental error.

These results indicate that both silver inks and deposited copper are competitive materials. Though silver inks are considerably less conductive, they are competitive by using more material, and can be competitive when using at 1 mm line widths. On the other hand, deposited copper has clearly superior conductivity, and can work with much less deposited material than silver and with narrower line widths. Thus, deposited copper can be used for thinner and narrower dipoles and achieve good efficiency using less material.

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