An Embedded UHF RFID Label Antenna for Tagging Metallic Objects

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Abstract

The drill strings used in oil drilling have a limited life in that a section may be used 400 times or until the diameter reduces 20 mm from wear against the surrounding rock. RFID labelling the pieces of the drill string allows the recording of usage and location data at a particular depth of the drill head, aiding in the planning of a rotation scheme, so that any one particular section is not constantly at a position of high stress.

Such RFID tags embedded in metal may be used for other metal asset tracking applications. Previous work [1,2] has been performed at HF frequencies but there is increasing interest in UHF frequencies as the frequency of choice for object tracking [2].

In this paper it is shown that suitable antennas can be made from capacitor structures sensitive to electric fields perpendicular to the metal surface.

An HFSS simulation environment for antenna applications was used to relate simulated results to known empirical results from both publications and their own experiments. Both the simulations and the measurements indicated that the antenna concept is suited to the application.

1. Introduction

A. The Problem

RFID is gaining increasing popularity in the identification of objects in the various supply chains around the world. Research into consumer product packaging (CPG) to find novel ways of integrating RFID labels is an active area of research.

Under the spotlight of item, case and palette level labelling has developed a number of challenges related to developing RFID antennas suitable for labelling metallic objects, objects filled with fluids and such barriers to radiation at the UHF region because these materials affect antenna performance. It is evident that new antenna designs are needed for identification of items manufactured with materials that affect the performance of antennas.

Interest in the analysis of electric field coupling to Radio Frequency Identification (RFID) antennas placed on or against metal, and some informal measurements based on some assembled structures, had suggested that the electric field coupling mechanism might be suitable for use in small RFID labels placed on or against metal, and excited in the far field by UHF RFID readers.

Potential application for such an antenna design lies in the labelling of “drill strings” used in oil drilling. These drill string pieces vary in size from 10" to 42" in diameter and are of course made from steel. The RFID tag is to be located in a 1" diameter hole at a depth below the surface of at least 10 mm after wear has occurred.

This problem has been addressed in the past by embedding U shaped ferrite cores in depressions in the metal, and exciting the connected RFID chips through the creation of tangential magnetic field sat 13.56 MHz, some of which is encouraged to enter the hole by the high permeability of the aforementioned cores.

B. Translation to UHF

The problem of RFID labelling of large metal objects previously approached as described above by an HF technology [1] has been translated to UHF by attempting to promote electric field between the antenna and its metal surround rather than attempting to promote the tangential magnetic field to dip down into the “hole” containing the RFID tag.

C. Antenna Construction

The antenna of interest consists of a top circular plate small in diameter up on a dielectric substrate, with the sides and base of the substrate copper clad to form a cylindrical tub. This capacitive plate is connected to the edge of the tub by an inductive track. The dielectric substrate used had a thickness of 3 mm, a diameter of 20 mm, and a relative dielectric constant of 3, with 1 oz. copper (35 microns). The top plate was 17 mm in diameter, and the spiral track was notionally 0.5 mm in width with 0.5 mm spacing (refer to Figure 1 and Figure 2).

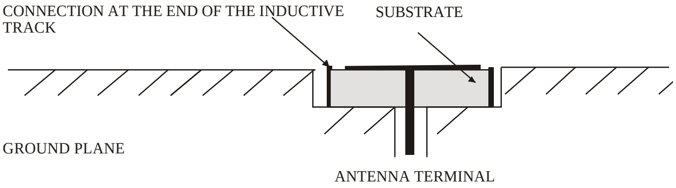

Fig. 1 Antenna structure (planar view)

The region where the track joined the top circular plate was filled in with copper tape and solder to raise the resonant frequency (reduce the inductive track length) to within the 902-928 MHz band.

The proposed RFID chip connection was chosen to be at the base between the bottom of the tub and a via to the centre of the top plate. For this investigation a panel mount SMA connector was used with a 1.25 mm diameter centre pin (via) to provide a connection to those nodes.

2. SIMULATION

The circuit was simulated in HFSS using the default FR4 and copper library values. Perfectly matched layers (PML) surrounding a vacuum box were used for radiation calculations rather than a radiation boundary. The default thickness of the PML boxes being one third the smallest dimension of the box was maintained, and the box was arranged so that all antenna parts were at a distance from the boundary of $1/\beta$ of the lowest frequency of interest (800 MHz) and a minimum radiating distance of 60 mm was chosen accordingly. To gain accurate results with a radiation boundary the boundary needs to be wavelengths away from the antenna which results in a lot of meshes in the vacuum surrounding the antenna, and the (large) boundary requires a fine mesh itself. The PML methodology developed results in a much smaller region around the structure as well as smaller surfaces on the boundary for radiation calculations (this boundary is selected as the infinite sphere although it was not spherical). An initial mesh was chosen at $\lambda/10$ and the dielectric and copper layers had length based mesh operations (seeding) assigned with the maximum size being

$$0.47\lambda / 61$$

This maximum mesh length value was derived from Balanis'[3] antenna experiments and works well for finite element analysis where a balance between simulation time and resources versus accuracy is desired – certainly suitable for practical work. The classic dipole of Balanis (0.49λ length, 0.005 lambda radius) was used to develop this simulation methodology with very close results for "61 segments". Figure 2 shows a top view of the antenna structure.

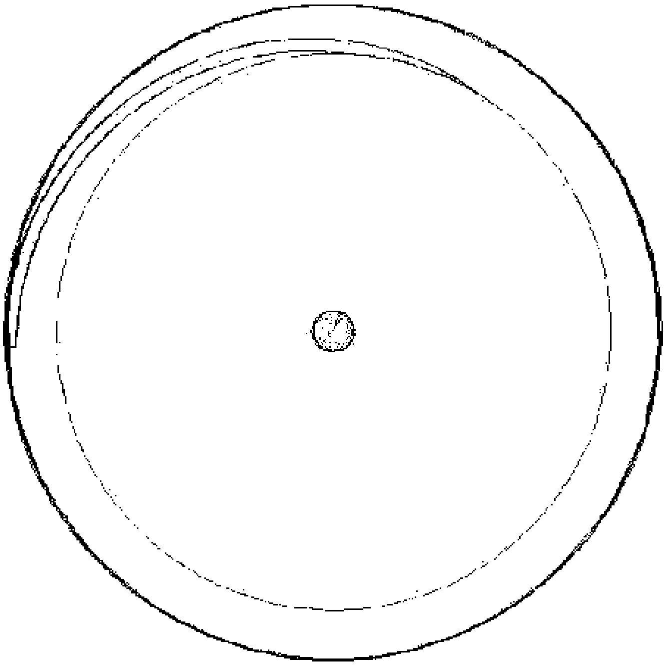

Fig. 2: Outline of the plate antenna, showing inductive track connecting centre plate to surrounding tub metal (top view).

Figure 3 shows the simulated resistance versus frequency of the intrinsic parallel tuned circuit in a linear plot.

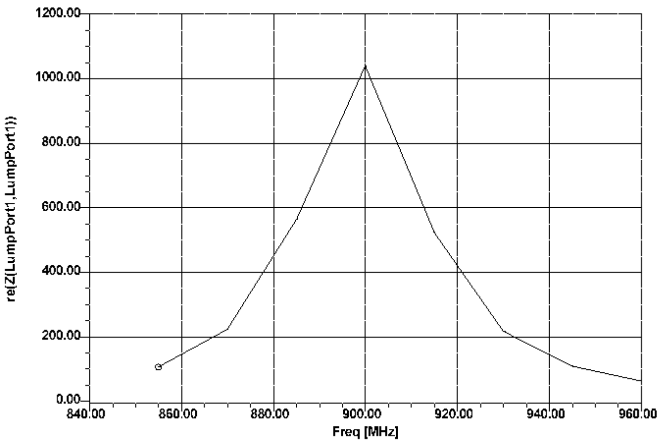

Fig. 3: Simulated real part of antenna impedance (ohms vs. MHz).

Figure 4 shows the radiation patter of the antenna obtained using the simulation software.

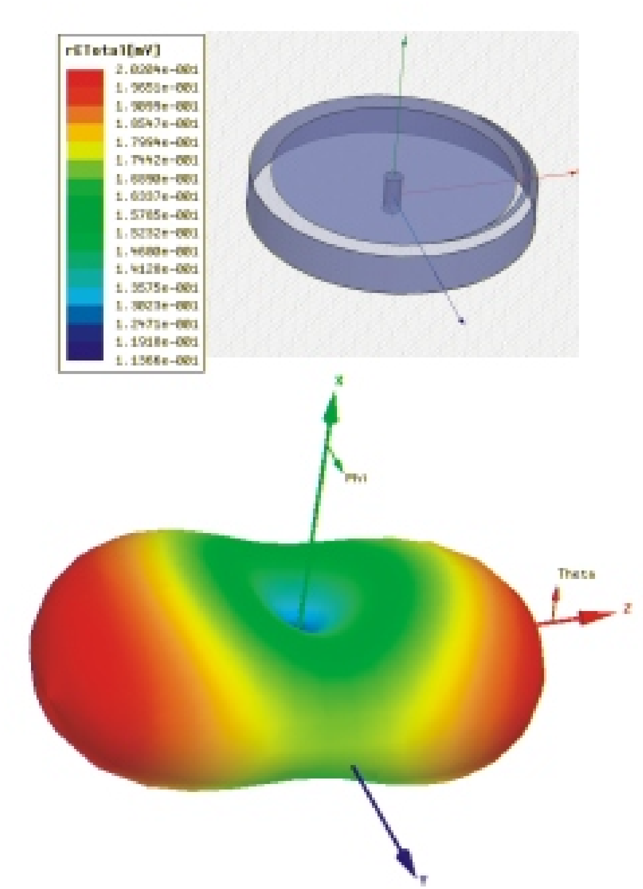

Fig.4: 3D Polar plot of the radiation pattern obtained from simulations.

3. MEASUREMENT PROCEDURE

Impedance/admittance measurements were performed with the antenna embedded into a ground plane, with a hole in the ground plane, keeping fields away from instrument cables. The reference plane was set to the base of the SMA connector (at the panel mount plane) to represent where a chip could be protectively located. S_{21} measurements between the plate antenna and a monopole field creation antenna were also performed above the ground plane, with a distance between the monopole and plate antenna centre of 205 mm (Figure 5).

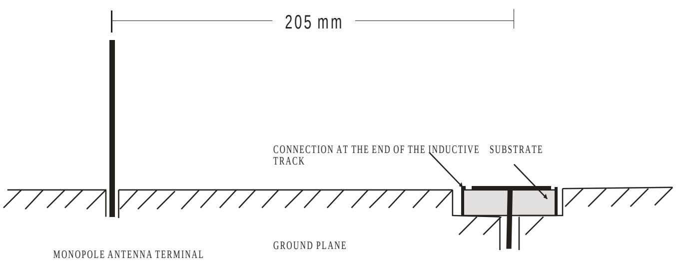

Fig. 5: Measurement arrangement.

The magnitudes of S11 for the field creation monopole (in a 50 ohm system) were -13.15 dB at 884 MHz, and -9.12 dB at 919 MHz.

4. MEASURED RESULTS

The antenna exhibited, as expected, parallel resonance, and as the impedance (loss) was much larger than 50 ohms, the trace was on the Smith chart periphery and thus points around the resonance (far right hand side of chart) fluctuate and cannot be trusted. The susceptance versus angular frequency (in radians per second) was plotted over a wide enough span to ensure the susceptance (1/reactance) measurements were stable and away from the "crowded" far right region. From the susceptance equation of a parallel tuned circuit,

$$jB = j\omega C - j/(\omega L),$$

the slope of the susceptance versus angular frequency plot around resonance is $2C$, which was found by "line of best fit" ignoring values near the resonance, and the resonant frequency taken to be where this line crossed zero susceptance (x-axis intercept).

The value for C was found to be 8.8 pF, which for a resonant frequency of 919 MHz yielded an inductance of 3.4 nH.

This parallel circuit was then loosely coupled to a network analyser by removing a small amount of copper (and the solder) from where the SMA centre conductor connected so that the centre conductor and top plate were capacitively coupled. The result was that the circuit resonated at a lower frequency but was an effective series circuit (detuned short), and the coupling could be arrange for the resistance at resonance to pass through 50 ohms (the Smith chart centre, Figure 6). The value of the coupling capacitor is not required to be known, only the resistance at the frequency of resonance.

The following calculation assumes the following; the substrate loss at the new lower frequency is equivalent to the loss at the frequency of interest (the substrate is suitable for the frequency of operation and is not being "pushed" such that losses are not highly frequency dependent); and the copper losses are constant (the difference in frequency is not sufficiently great so as to require manipulation of the losses). The reason for these assumptions was that the losses were not sought to be separated but rather the intrinsic Q (quality factor) of the antenna needed to be known of the first order calculations for suitability of an antenna for RFID.

The combined losses were represented by R, the resistance of a parallel tuned circuit at resonance. To extract this loss, the parallel L and C where combined at the lower loosely coupled frequency to yield an effective inductance L_{eff}, as the circuit was below the intrinsic resonance thereby inductive. L_{eff} and

R where then transformed to a series equivalent circuit at the lower frequency by the relation

$$R = (Q^2 + 1)\, r,$$

where r was the resistance value at the lower resonance, and

$$Q = R / (\omega\, Leff).$$

Solving for R results in a quadratic with the higher of the two solutions being the one chosen. R was found to be 885.12 ohms, which includes the dielectric and copper losses along with the radiation resistance. Thus, the intrinsic Q of the original parallel resonant circuit at its original resonant frequency was calculated to be 45.1.

Transmission measurements between the antenna mounted above a ground plane and a resonant 1/4λ monopole (distance 205mm) above the same ground plane gave a transmission loss S_{21} of –29.6 dB at the loosely coupled resonant frequency of 884 MHz.

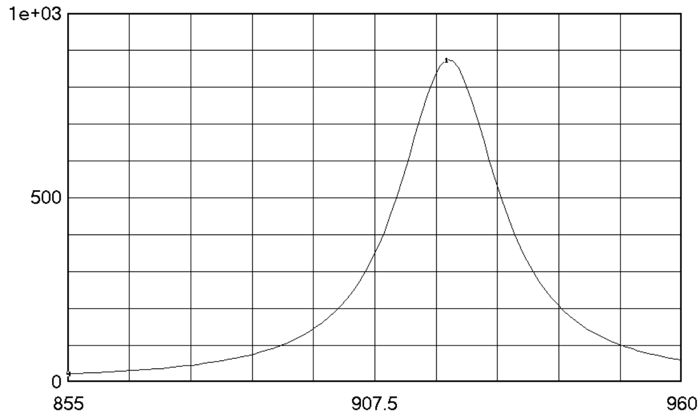

Fig. 6: Measured real part of antenna impedance (ohms vs. MHz).

Figure 6 shows the measured resistance versus frequency of the measured parallel tuned circuit in a linear plot (which were on the right hand side periphery of the Smith chart).

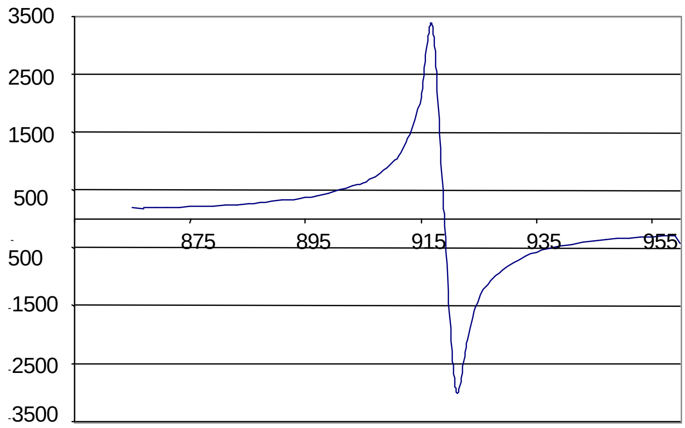

Fig. 7: Measured reactance of antenna impedance (ohms vs. MHz).

Figure 7 shows the measured reactance of the antenna impedance. These values were obtained from measurements at the periphery of the Smith's Chart and thus do no represent an accurate picture of the antenna's reactance values. However better results can be obtained by using the model parameter values of C and L evaluated previously in this Section.

Figure 8 shows the loosely coupled configuration, the goal was to be close to the centre of the Smith's Chart for accurate measurement of resistance.

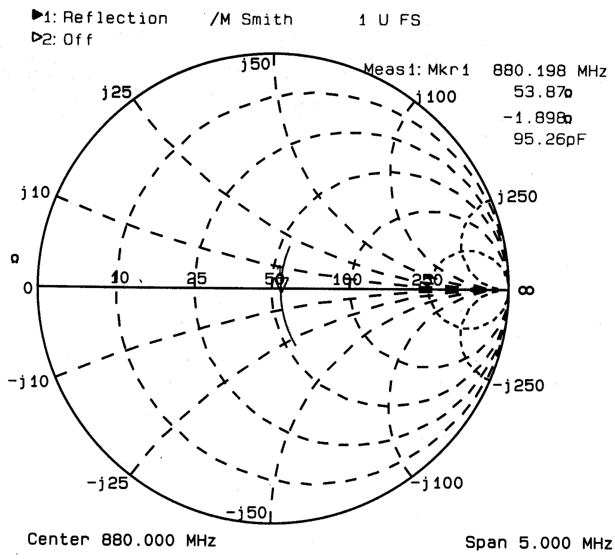

Fig. 8: Measured antenna impedance.

5. CONCLUSIONS

The transmission loss between the antennas, when adjusted for a realistic interrogator to label distance of 1 m and end EIRP of 4W suggests that the available source power from the antenna will be 160 microwatts, which is more than sufficient to power an RFID label at this distance.

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