# A Low Cost Flexible Passive UHF RFID Tag for Sensing Moisture Based on Antenna Polarization

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***Abstract*—Cost optimization and performance are the continuous improvement areas in any technology. In this paper a flexible dipole antenna on a passive UHF RFID tag is designed on an inexpensive paper substrate which can sense the moisture based on the polarization of the antenna. An inexpensive paper substrate and copper (Cu) layer are used for the flexibility and the optimization of manufacturing cost. The dipole antenna is matched with the complex conjugate of the power harvesting circuit of the Higgs2 Integrated Circuit (13.88 -j143.6 at the frequency of 915 MHz). The key characteristic of this design is the sensitivity of the antenna polarization on the passive RFID tag to the moisture content in the paper substrate. In simulations, the antenna is circularly polarized when the substrate is dry (relative permittivity, $\epsilon_r$= 2.38) and the antenna is linearly polarized when the substrate is wet (relative permittivity, $\epsilon_r$= 35.35). The read ranges of the fabricated dipole antenna (i.e., prototype RFID moisture sensor) are measured and the desired performance is achieved with overall tag dimensions of $0.144\lambda_0 \times 0.133\lambda_0$ where $\lambda_0$ is the free space wavelength at 915 MHz.**

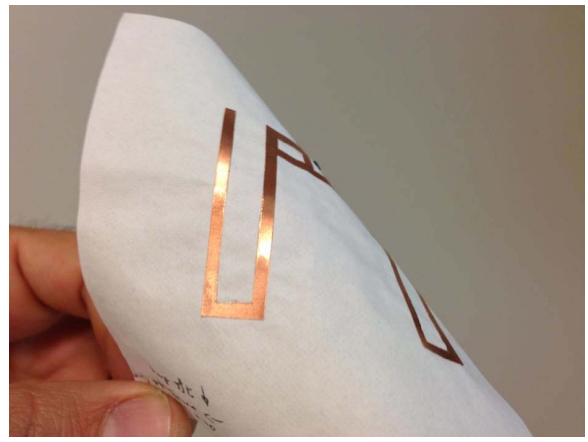

Fig. 1. The flexibility of the fabricated antenna

## I. Introduction

To minimize the cost of a sensor which can sense the wetness remotely is a big challenge. There are many solutions based on different technologies. In reference to [1] the paper-based semi-passive RFID was used which has no internal battery but a built-in energy conversion sensor. Some other technology uses passive LC resonating sensor tag [2], plurality of conductor pairs [3], RFID tag activation by a fluid [4], RFID transponder comprising sensor element [5], waste detection system [6], electric voltage difference [7] and hygroscopic polymer [8] for low cost sensing. The objective of the new technology is to minimize the cost and to increase the ease of use.

In this paper the cost is reduced by using very inexpensive paper substrates, Higgs2 IC and copper as a conductive layer. Since it is fabricated on paper, it is very flexible (Fig. 1) to facilitate the applications where flexibility is required. Furthermore the permittivity of the paper substrate is changed with the addition of moisture [9]. Based on this principle a new antenna is fabricated where the dipole antenna uses the polarization to differentiate whether it is dry or wet. In measurements the antenna actually uses the ratio of the reading distances of the differently oriented antennas to sense the moisture in paper [10]–[16].

## II. Functionality and Design

The dipole antenna is designed to sense the moisture from a certain reading distance. But the reading distance depends on the moisture absorbed by the paper substrate. Because good matching depends on the designed permittivity of the paper that is changed when it absorbs the moisture. That's why based on the presence of moisture in the paper substrate the dipole antenna is either circularly polarized or linearly polarized. The RFID Integrated Circuit (IC) is used for power harvesting only.

### A. Substrate Selection

An inexpensive substrate Strathmore Marker 500 Series, acid-free, 100% cotton based paper with thickness of 56 microns was used. The relative permittivity and loss tangent in different scenarios (dry and wet) were measured with the help of a RF Impedance/Material Analyzer E4991A (1MHz-3GHz) (Fig. 2). Five samples of the same paper substrate were tested and the average was used for the simulation. First we measured the dry paper and the water was added to the paper to make it wet. Then we measured the wet paper. The average of relative

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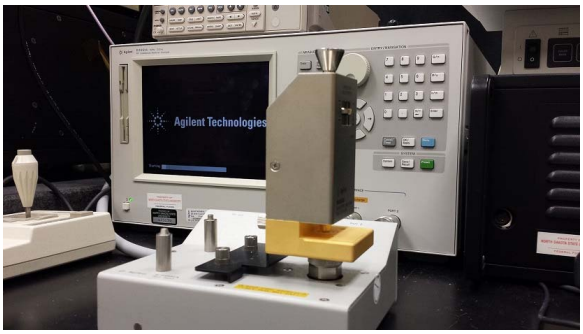


Fig. 2. RF Impedance/Material Analyzer E4991A (1MHz-3GHz)

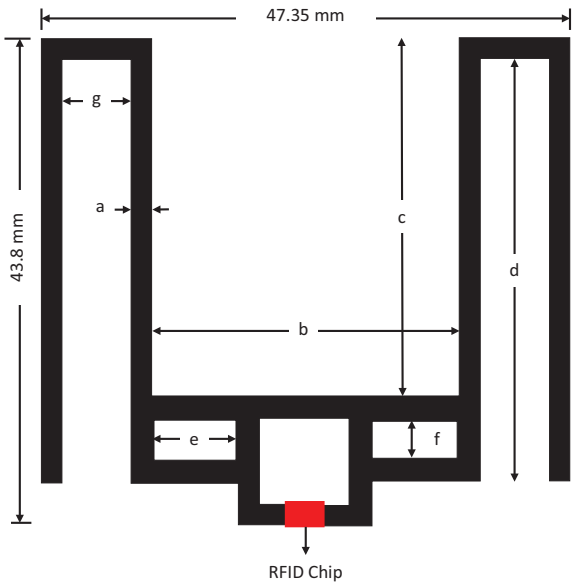


Fig. 3. Dimension of the Antenna; a= 2 mm, b = 27.35 mm, c = 32.35 mm, d = 38 mm, e = 7.6 mm, f = 3.65 mm, g = 6 mm

permittivity and loss tangent of the paper substrate are shown in Tables I and Table II for various values of moisture.

TABLE I
AVERAGE RELATIVE PERMITTIVITY ($\epsilon_r$) OF THE PAPER SUBSTRATE

| State | Sample | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | Average |
| Dry | 2.30 | 2.40 | 2.33 | 2.45 | 2.42 | 2.38 |
| Wet | 34.5 | 37.4 | 36.6 | 33.7 | 34.55 | 35.35 |

TABLE II
AVERAGE LOSS TANGENT OF THE PAPER SUBSTRATE

| State | Sample | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | Average |
| Dry | 0.061 | 0.067 | 0.063 | 0.072 | 0.067 | 0.066 |
| Wet | 0.186 | 0.192 | 0.182 | 0.175 | 0.205 | 0.188 |

## B. Antenna Dimension

The antenna was designed having the dimensions of 47.35 mm × 43.8 mm on the paper substrate and minimum copper

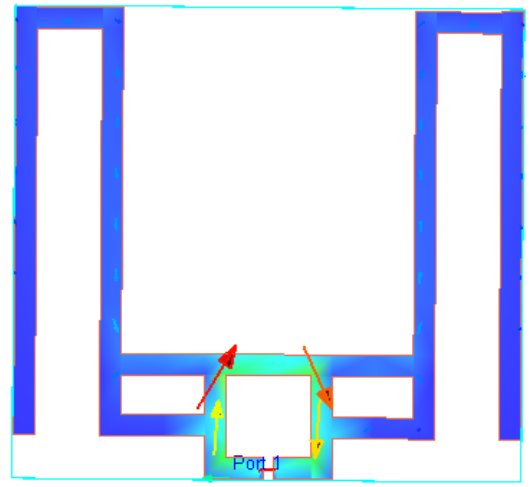


Fig. 4. Current distribution when relative permittivity $\epsilon_r$ = 2.38, loss tangent = 0.066

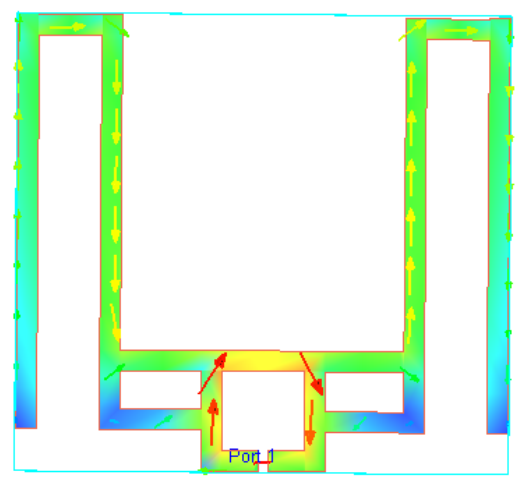


Fig. 5. Current distribution when relative permittivity $\epsilon_r$ = 35.35, loss tangent = 0.188

was used to minimize the cost of the antenna. The antenna was designed as a dipole antenna with a 0.26 mm gap between two poles. Alien Higgs2 RFID IC was used in between two poles which are responsible for power harvesting purpose. The dimensions of the antenna are shown in Fig. 3.

## C. Fabrication

The antenna was manually cut from a 2 inch wide Cu tape using an Exacto knife under a microscope (Leica S8 AP0). The paper backing of the tape was then removed and the antenna was taped on the paper substrate. Higgs 2 was simply soldered to the leads.

## D. Simulation Results

The method of moments was used to simulate the antenna. The impedance of the Higgs2 IC depends on the frequency. We


Fig. 6. Alien ALR-9610-BC RFID reader


Fig. 7. Alien ALR-9610-BC RFID reader Antenna

simulated the antenna to match the complex conjugate of IC impedance to achieve good matching at the desired resonant frequency. We used a linear sweep frequency from 800 MHz to 1.1 GHz. Based on the current distribution in simulation results the antenna was circularly polarized when it is dry ($\epsilon_r$ = 2.38, loss tangent = 0.066) (Fig. 4) and is linearly polarized when it is wet ($\epsilon_r$ = 35.35, loss tangent = 0.188) (Fig. 5).

### *E. Measurement Results*

The read range of five sample moisture sensors were measured in both the horizontal and vertical positions at different reading distances using an Alien ALR-9610-BC RFID reader (Fig. 6) and reader antenna (Fig. 7).

Based on the ratio of the horizontal reading distance to the vertical reading distance the presence of the moisture in the paper can be sensed. All numbers are reading distances in cm, except the ratios. Parallel ($\|$) means reader antenna parallel to the sensor and perpendicular ($\perp$) means reader antenna perpendicular to the sensor. Horizontal means signal from the horizontally polarized reader antenna and vertical means signal from the vertically polarized reader antenna. Readings are consistent within 40 deg. deviation from the normal (i.e., 80 deg. field of detection). The results are shown in the Tables III and Table IV and it is shown that the perpendicular and parallel H/V ratio for the wet case is 2.7 and 4.4 times larger, respectively, than the dry case. This change in the H/V ratio is caused by the moisture in the paper substrate and indicates that the sensor is working properly.

TABLE III
READING DISTANCE MEASUREMENT WHEN ANTENNA IS DRY

| ID | Horizontal | | Vertical | | H/V Ratio | |
|---|---|---|---|---|---|---|
| | $\|$ | $\perp$ | $\|$ | $\perp$ | $\|$ | $\perp$ |
| 8C99 | 549 | 549 | 213 | 183 | 2.57 | 3 |
| 6203 | 457 | 457 | 152 | 152 | 3 | 3 |
| 0BC4 | 549 | 549 | 183 | 183 | 3 | 3 |
| 35DF | 594 | 594 | 305 | 274 | 1.95 | 2.17 |
| 9916 | 655 | 655 | 274 | 366 | 2.39 | 1.79 |
| Average | | | | | 2.58 | 2.59 |

TABLE IV
READING DISTANCE MEASUREMENT WHEN ANTENNA IS WET

| ID | Horizontal | | Vertical | | H/V Ratio | |
|---|---|---|---|---|---|---|
| | $\|$ | $\perp$ | $\|$ | $\perp$ | $\|$ | $\perp$ |
| 8C99 | 549 | 549 | 61 | 76 | 9 | 7.2 |
| 6203 | 457 | 457 | 61 | 61 | 7.5 | 7.5 |
| 0BC4 | 549 | 549 | 30 | 91 | 18 | 6 |
| 35DF | 518 | 518 | 46 | 61 | 11.33 | 8.5 |
| 9916 | 549 | 549 | 46 | 91 | 12 | 6 |
| Average | | | | | 11.57 | 7.04 |

## III. DISCUSSION

Many noteworthy comments cane be made about the results in Fig1, 3-6 and Table III, IV.

1) It is the first low cost moisture sensor which works based on the polarization.
2) As the antenna is fabricated on paper, it is very flexible compared to other solutions of low cost moisture sensors.
3) The dimensions in Fig.3 are 47.35 mm $\times$ 43.8 mm ($0.144\lambda_0 \times 0.133\lambda_0$) which are comparatively smaller than other commercially available tags.

## IV. CONCLUSION

In this paper we investigated a cost effective solution to sense moisture in an absorbing substrate using the polarization of a printed antenna on a passive RFID tag. In particular, a new antenna design with a polarization sensitive to the permittivity of the antenna substrate was presented. This sensitivity was then used to measure the moisture in a paper substrate and it was shown that the read-range of the sensor changed with moisture content. This makes this antenna design useful for sensing moisture without the requirement of a battery.

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