Passive RFID Ammonia Sensor Utilizing Carbon Nanotubes

A low-cost chemical sensor

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Abstract—**This paper describes the design of a low-cost patch antenna with an RFID chip and implanted functionalized carbon nanotubes, which behaves as a light-weight ammonia gas sensor. After choosing a cheap, flexible substrate to build the patch antenna, a folded patch antenna was later used to achieve compact size. Carbon Nanotubes are functionalized with polyaminobenzene sulfonic acid (PABS), to make them more sensitive to ammonia. After depositing the CNTs and integrating a UHF GEN2 RFID chip with the antenna, measurements were taken using a high-sensitivity RFID reader. Data shows a shift in operational frequency of the RFID tag after the antenna is exposed to ammonia.**

Keywords: CNT, patch antenna, HFSS, RFIC, RFID, ammonia sensor, gas sensor

I. Introduction

Current day gas sensing technology has become increasingly sophisticated. Although very sensitive gas sensors are common in the market, the $400-$600 price range continues to be a deterrent to wide spread use of this type of sensors [1]. This paper proposes a solution to build a cheap wireless ammonia gas sensor that could be deployed to the battlefield or places with elevated risk of terrorist attacks (ammonia gas has been proven to be present in improvised explosive devices), among other cases where sensing this gas is necessary.

The principle of operation of the proposed sensor is to track the frequency of operation of an EPC Gen2 RFID chip with a patch antenna. This antenna is loaded with functionalized single-walled carbon nanotubes (SWNTs), which change their conductivity when exposed to ammonia. A characterization study of a similar CNT sample was presented in [2], although for this prototype the CNTs are functionalized with PABS to increase their sensitivity to ammonia. It is possible to track the frequency change (due to load impedance variation) in the communication of the RFID with a high-sensitivity RFID reader.

Preliminary studies of a similar sensor show that a large frequency shift can be experienced when the antenna-implanted CNTs sample is exposed to ammonia [3]. The current project aims to use a new folded patch antenna to achieve a portable size, with a more durable physical form (low-loss RO3003 substrate with copper top and bottom layers, and metal vias). Although not as cheap as inkjet printed antennas on flexible glossy paper, PTFE substrates offer durability and are ideal for open field use.

The RFID IC used was chosen to operate in the 860-960 MHz band described in ISO 18000-6 [4], and a high-sensitivity reader is used to interrogate this tag from far-field.

II. Design of Gas Sensor

A. First step: modeling the patch antenna

To be able to use an RFID chip operating in the 860-960 MHz range, a patch antenna to be fabricated on flexible substrate by inkjet printing was first designed and simulated using Ansys HFSS. The required dimensions were approximately 16 cm by 6 cm, and it was decided that a smaller antenna was needed. A folded patch antenna with meandered slots that operated in our desired frequency range was provided to our team. The size of this new patch antenna was reduced to 5.1 cm by 3.3 cm, a considerable decrease. A 3D model was constructed using HFSS to choose the optimal location for placing the functionalized carbon nanotubes. Fig. 1 shows the graphical representation of this antenna.

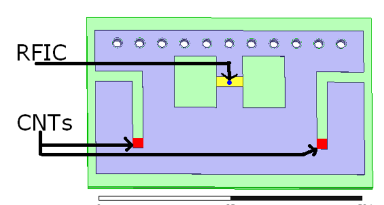

Figure 1. HFSS model of folded patch antenna.

By folding the patch antenna with the help of the vias and using meandered slots an approximate 3x size reduction is achieved. Similar miniaturization techniques are described in [5]. Note that the dielectric constant for the glossy paper substrate used in the simulations described above are comparable because $\varepsilon_r = 3$ for RO3003 material [3][6].

After looking at the simulations for this folded patch antenna, two locations for the CNTs were discussed: the

90° bent in the slot or the bottom portion of the slot. The later was chosen because a larger current concentration engulfed that area. Basically high-current concentration points on the slots will guarantee that the CNT coating will work as a lossy metal between conductive copper areas.

B. Carbon nanotube solution

To increase the carbon nanotubes' sensitivity to ammonia, the polymer polyaminobenzene sulfonic acid is covalently bonded to SWNTs via amide functionalization [7]. This process also allows for a water-soluble compound, which can be either printed using inkjet technology, or dispensed on top of the desired surface. Fig. 2 shows the PABS functional group that is attached to the SWNTs is sensitive to NH_3. NH_3 molecule removes a proton (H^+) from the side-chain oligomers that, in turn, causes an electron to be transferred between the side chain and the SWNTs. This process reduces the conductivity of the PABS-SWNTs ensemble because the electrons added to the semiconducting SWNTs refill the valence band.

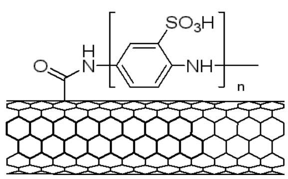

Figure 2. PABS-SWCNTs structure

A solution of PABS-SWNT with a concentration of 5mg/mL in water was used for this project. This solution was sonicated for 3 hrs to guarantee homogeneity, and then deposited on the specific locations marked in Fig. 1, by means of a small brush. Subsequent depositions followed by small curing periods in a lab furnace (to evaporate the water in the solution and expose the CNTs) for 15 times resulted in a dark-colored layer between the copper regions. Several other deposition techniques, such as chemical vapor deposition (CVD) and thin films have been studied in [8] and [9], respectively.

C. RFID chip integration

A NXP RFID IC with complex impedance Z_{IC} = 16-j122 Ohms was used for this project, but since the patch antenna was provided after being manufactured, it was not possible to match the antenna's impedance to the RFID's. Some degradation of the transmitted signal from the RFID to the reader is to be expected because of unwanted reflections. The RFIC was attached to the location detailed in Fig. 1 using silver epoxy. Fig. 3 shows the relative size of the complete sensor prototype.

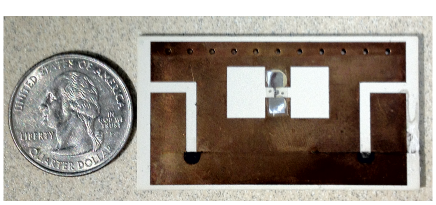

Figure 3. Relative size of fabricated sensor prototype.

III. MEASUREMENT SETUP

With the antenna ready for measurement, a supply of different concentration ammonia solutions was needed. Instead, commercial off the shelf 10% ammonia hydroxide was used. A small piece of paper towel was damped in about 6 mL of this solution at the time of the test.

A closed plastic container with 210 cm^3 volume was used to hold the antenna and the ammonia content. A Voyantic Tagformance RFID reader was used to interrogate the chip, with a circularly polarized antenna with a gain of 6 dBi. The reader and tag are spaced 1 lambda into far-field, or 101 cm, where the far-field region is calculated using equation 1, and it is 68 cm.

$$d_f = \frac{2 \times D^2}{\lambda}$$ Equation 1

The area surrounding the experiment is covered with absorbing foam. Fig. 4 shows the setup.

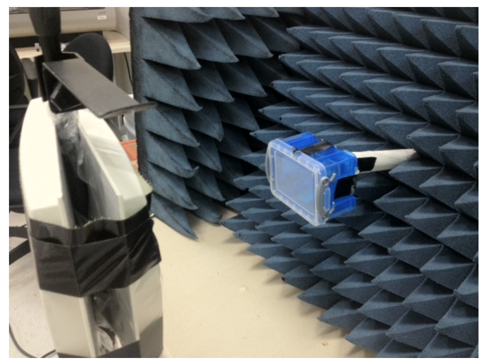

Figure 4. Lab measurement arrangement.

IV. ANALYSIS OF RESULTS

The Tagformance RFID reader has a software GUI that can plot the results as it performs the tests. It will report the smallest power it has to send to receive a backscattered signal from the tag, for discrete frequency values over a range. It is assumed that the lowest transmitted power needed to power the tag on and to receive a backscattered signal from it will occur at the resonant frequency of the tag. Fig. 5 shows the results as shown in the Tagformance GUI.

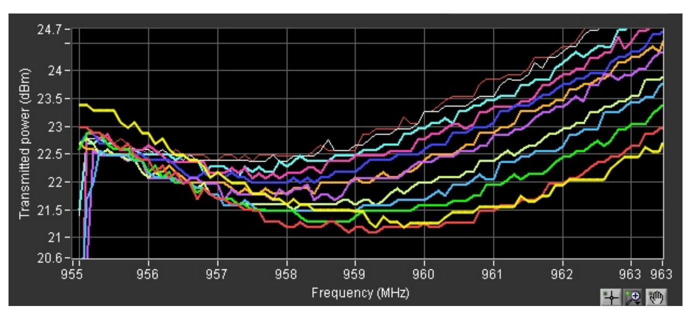

Figure 5. f_{res} after exposure to ammonia.

These graphs were taken with a time interval of approximately 3 min, and they appeared from bottom to top with increasing time. After looking carefully, there is a tendency for the frequency to shift from 959.5 MHz to 957 MHz with time.

Note that the ideal operational frequency of the tag is 915 MHz, so a probable explanation for this jump from 915 MHz to 958 MHz is that the antenna had a resonant peak a bit off from the desired value.

The data collected with the Tagformance reader was also plotted in Excel, shown in Fig. 6.

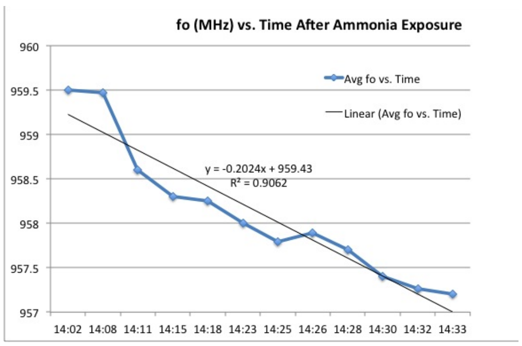

Figure 6. Frequency shift versus time.

A few key observations can be made here. The time intervals for which data was taken were not constant, because the maximum power and the resolution of the Tagformance were modified during the test. Otherwise, a decrease in the frequency of operation can be extracted from this plot, although the previous studies cited here had found a larger impact of the SWNT load variations on the frequency.

Even when the test took approximately 31 minutes to complete, it is difficult to point out a saturation value. The curve fitting was expected to be exponential, reaching saturation. Nevertheless, the R^2 results showed that a linear fitting was more appropriate.

Also, for a 1 MHz shift to occur, there is a required settling time of approximately 20 minutes, which might be excessively long for a critical application, like the detection of IEDs.

V. CONCLUSIONS

A prototype antenna was built using a patch antenna on a PTFE substrate, with deposited PABS-functionalized single-walled carbon nanotubes (PABS-SWNTs), and an integrated RFID chip. After fabricating the prototype, a test setup was used to collect data from the interrogation of the RFID tag integrated in the patch antenna.

For the folded patch antenna-RFID sensor, a resonant frequency shift of about 2.5 MHz was recorded after approximately 22 min.

Using a PTFE substrate (RO3003) to fabricate the folded patch antenna has the advantage of resulting in a more durable antenna, which could potentially be used out in the field. This benefit comes at a higher cost compared to inkjet-printed antenna, because the PTFE design has to be sent out to a manufacturer for fabrication. Higher volumes can reduce the per-unit cost of fabrication.

The short distance to reach the far-field region is a limitation to this prototype, therefore future studies should address this shortcoming. A solution to this issue could be using an active RFID tag, which would extend its range of operation.

Because ammonia solutions with different concentrations were not available, it was impossible to determine the concentration (in ppm) that this chemical sensor is able to detect accurately. This project serves as a proof of concept that this technology can be implemented at a relative low cost.

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