A Novel Inkjet-Printed Passive Microfluidic RFID-based Sensing Platform

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***Abstract*—This work introduces a first-of-its-kind wireless passive sensing platform combining RFID, microfluidics and inkjet printing technology that enables remote fluid analysis which requires as little as 3 uL of fluid. The tag is fabricated using a novel rapid, low-cost, and low-temperature additive inkjet process making the tag disposable. However, even with its disposable nature, the tag exhibits repeatability and long-term re-usability in accurately detecting water, various alcohols, and % content of water/alcohol mixtures. The proposed platform could find a multitude of applications ranging from water quality monitoring to wearable biosensing/bioanalysis and perishable liquid storage tracking.**

***Index Terms*—Inkjet Printing, Microfluidics, RFID, Antennas, Wireless Sensors, Passive Sensors**

I. Introduction

Microfluidics have become a valuable tool over the past decade to manipulate, analyze, and interact with tiny amounts of liquid. Before microfluidics, processes such as bio-assays and water quality analysis required large amounts of liquid ranging from several milliliters to several liters. However, the fabrication of microfluidic systems allows fluid analysis to be performed on samples in the order of micro to picoliters due to the integration of electronics, fluidic manipulation structures, and micron sized fluid channels on a single chip.

Microfluidic devices have typically been fabricated utilizing cleanroom processing which require harsh chemicals and high temperature and pressure bonding processes. However, recent advances in microfluidics have demonstrated rapid, low-cost methods for fabricating these systems utilizing low temperature bonding of laser cut channels, or wax impregnated paper to guide fluid through capillary action [1], [2]. However, one of the current issues with low-cost microfluidics is integrating electronics while keeping the devices low cost as the deposition and patterning of conductors and sensors still requires cleanroom processes.

In this paper, we propose a novel approach which utilizes inkjet printing to rapidly fabricate electronics and low temperature bonding layers for low-cost microfluidics to enable a passive RFID-based microfluidic sensing platform. Inkjet printing is utilized as it is a rapid additive process which can deposit a wide variety of materials at low temperature. The proposed ”zero power” inkjet-printed sensing platform can be utilized in large-scale distributed water quality measurement, process monitoring, and biomedical analysis.

II. Theory of Operation

Sensing of fluids utilizing RF has been investigated in several works which commonly utilize transmission lines or resonators loaded by a fluid cavity [3], [4]. To enable wireless sensing of fluids, a cable-less method is proposed in this work. Fluid sensing using the proposed microfluidic RFID tag works by varying a capacitive load at the ends of a meandered dipole by utilizing small amounts of fluid in a microfluidic channel. Capacitive gaps which are areas of high field concentration, as shown in Fig. 1, are placed across small microfluidic reservoirs through which the sensed liquid is flowing.

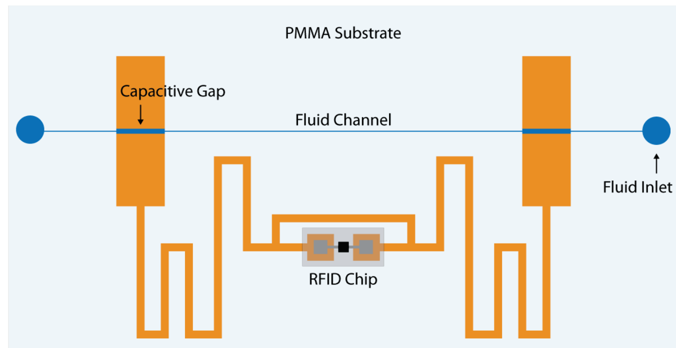


Fig. 1. Design of the microfluidic RFID tag which utilizes fluid-loaded capacitive gaps to change the electrical length of the antenna

At microwave frequencies, fluids exhibit large differences in their electrical parameters such as permittivity (ϵ_r), conductivity (σ), and loss ($tan\delta$). The common electrical parameters of various fluids used in this work are displayed in Table I. Due to the large variation in electrical parameters of different fluids in the RFID band (including permittivity, conductivity, and loss), large variations in gap impedance are achieved when different fluids, or mixtures of fluids flow through the channels.

TABLE I
Electrical parameters at 900 MHz and 300 K [5], [6]

Fluid	Re(Permittivity) ϵ'	Im(Permittivity) ϵ''
Water	73	5
Ethanol	15	11
Hexanol	3	2.5

The change in gap impedance changes the electrical length of the antenna which causes resonant frequency shifts in the RFID tag. Choosing the gap size is a critical parameter in the sensing range of the device. The gap size must be chosen so its capacitive impedance is several hundred ohms at the lower end of the permittivity range to be measured to create an rf open across the gap, and below 100 ohms at the higher end of the permittivity range to create an rf short which increases the electrical length of the antenna. If the gap is too small, the gap impedance is low and rf shorting of the signal, and thus sensor saturation occurs at very low fluid permittivities. The resonant shifts which are caused by varying the impedance of the capacitive gap are then detectable by a RFID reader, and through post processing, the electrical parameters of the fluid can be extracted. This method also has the advantage of real-time monitoring of the fluid parameters flowing through a specific tag or array of tags.

III. Printed Microwave Tag Fabrication

The RFID-based microfluidic tags proposed in this work are constructed in three steps. First, a silver nanoparticle based ink from Cabot Corp. is used to print the RFID antenna onto a paper substrate using a Dimatix DMP-2800 materials printer. After printing, the antennas are cured at 120 °CC for 30 min in a Thermo Scientific oven [7].

Next, the microfluidic channels are etched on a second substrate which will be bonded on top of the antenna. To avoid cleanroom processing, the channels and cavities are etched into 1.5 mm thick sheets of poly(methyl-methacrylate) using an Epilog Mini-24 laser etcher. The two fluid cavities, which are placed over the capacitive gaps in the antenna, are cut to be 0.75 mm wide by 6 mm with a depth of .5 mm. The channels, which connect the cavities together, are cut to be .3 mm deep by .15 mm wide. This gives the total volume of liquid within the fluidic system to be between 3 and 6 uL, which is approximately a ten times smaller volume than the average drop of water. In addition to the channels and fluid cavities, an extra cavity is cut out so that the RFID tag can be mounted on the antenna and packaged within the PMMA without being broken during bonding. The Alien Higgs 3 RFID tag is adhered using silver epoxy before step three.

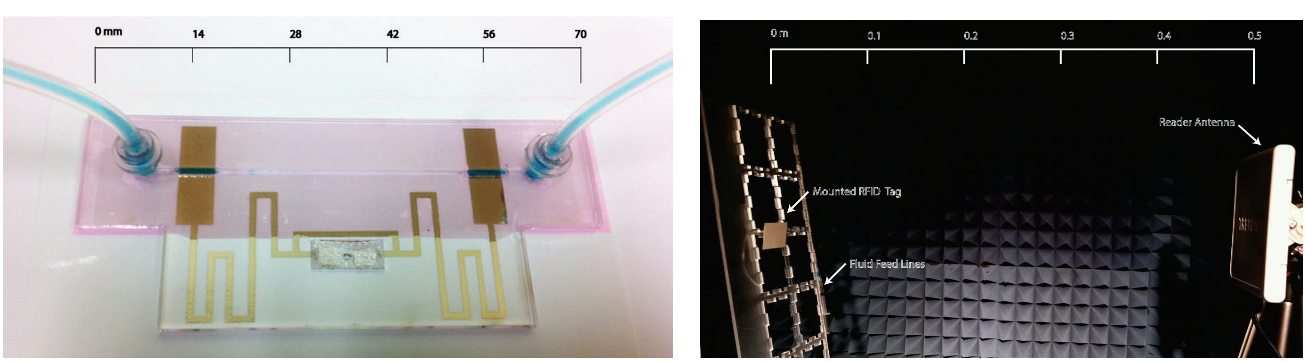
After etching of the fluid channels, the PMMA substrate is bonded to the paper substrate of the antenna to seal the channels. For this, an adhesive polymer which is optimized for inkjet printing on the Dimatix printer is used. An extremely thin polymer bonding layer which is 15 um thick is printed over the antenna. A thin bonding layer is important as the thin channels will clog if too much adhesive is used. The PMMA sheet with microfluidic channels is then aligned and pressed onto the antenna. The polymer is then cured at 80 °C which forms a watertight bond between the paper substrate and the PMMA. It is this polymer which restricts the fluids to only travel within the etched channels and cavities and not leak into the paper or out of the channels.

The complete process is performed under the glass transition temperature of most polymers of 120 °CC and without harmful chemicals or material waste. The estimated cost per tag at low volume is approximately 25 cents and a streamlined batch of tags can be fabricated in several minutes.

IV. Simulation and Measurement

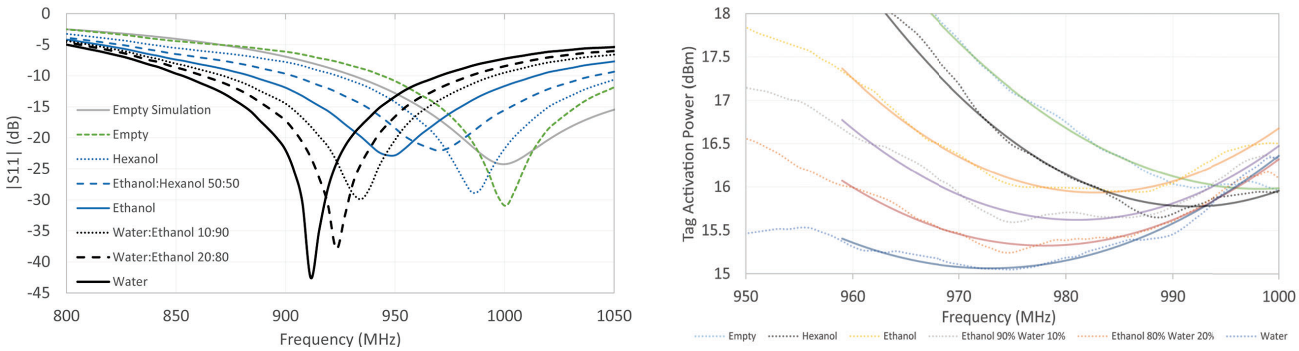
The microfluidic tags are designed to operate with the Alien Technologies, Higgs 3 EPC Gen-2 RFID chip in the readable range of the Voyantic Tagformance reader which is 800 1000 MHz. As the resonant frequency of the tag will only shift downwards when fluid is introduced into the channel, the resonant frequency of the tag is optimized without fluid in the channels using the CST frequency domain solver for 1000 MHz. To confirm agreement of the fabricated tag with the simulation, as well as quantify the resonant shifts the tag experiences with the introduction of different fluids, a cabled measurement of the return loss of the antenna is performed using a Rhode and Schwartz ZVA-8 VNA. The measured S-parameters are then re-normalized to the RFID chip impedance as displayed in Fig 3(a). The return loss shows matching at 1 GHz when the channel is empty which matches the simulation results. Various fluids including water, ethanol, hexanol, and mixtures of the three are then pumped through the fluidic channels while the return loss is measured. Distinct downward shifts in the resonance confirm that the fluidic channel is loading the capacitive gap on the antenna and increasing the electrical length. Large shifts of nearly 100 MHz are achieved in the cabled measurement. The shifts experienced in the cabled measurement are compared with simulation in Fig. 4 and the best fit curves show a difference below 6%. It can be noticed that even small changes in fluid mixtures such as increasing the water content in ethanol from 10 to 20% produce easily readable shifts.

Following cabled verification of the passive microfluidic tag, the Alien RFID chip is mounted on the tag and a wireless measurement setup is constructed as displayed in Fig. 2(b).



(a) (b)

Fig. 2. (a) Fabricated RFID-based microfluidic tag with printed antenna, laser-cut channel, and printed bonding layer, and (b) measurement setup for wireless measurements with the Tagformance RFID reader



(a) (b)

Fig. 3. (a) Cabled measurement of the microfluidic RFID antenna displaying resonant frequency with different fluids, and (b) wireless measurements of the passive tag with mounted Alien Higgs 3 chip utilizing the Tagformance RFID reader

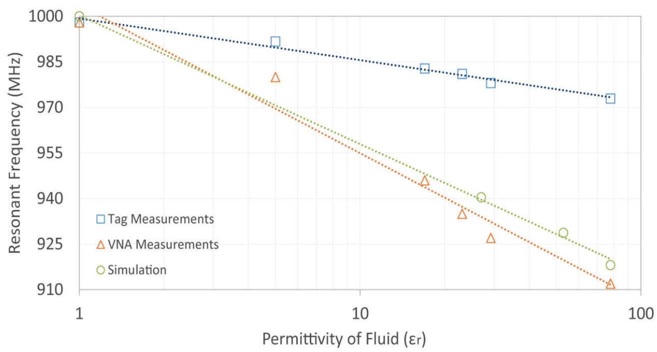


Fig. 4. Frequency shift of the tag versus fluid permittivity for simulation, cabled measurement, and wireless RFID-based measurement

The tag is placed 0.5 m away from the reader antenna of the Tagformance which interrogates the tag across the 800 1000 MHz band. The Tagformance returns data on power required to activate the tag, and the reflected power and phase versus frequency. Again, the tag is measured with an empty channel, and all of the fluids used in the cabled measurement. The data returned from the Tagformance which is shown in Fig. 3(b) displays the transmit power required to activate the tag versus frequency along with the second order curve fit in Matlab which is used to extract the resonant frequency. A clear downward shift in the resonant frequency is experienced as higher permittivity fluids are sent through the channel as is expected, and a the resonant shift versus fluid permittivity is plotted in Fig 4 against simulation and cabled measurement. It is noticed that the activation power slightly decreases with the higher permittivity fluids which is due the improving matching between the antenna and chip impedance. The T-match is designed so that optimal matching occurs when the antenna resonant frequency is 900 MHz. It is seen from Fig. 4 that the wireless tag exhibits lower shifts than the cabled measurement, and this is due to the variation in chip impedance over frequency which is not taken into account in the simulation or cabled measurement.

After all of the liquid measurements are performed, the tag is emptied and again measured. The extracted resonant frequency of the empty tag is within a fraction of a percent of the empty measurement before being filled with an array of fluids. This demonstrates a high degree of repeatability which is important in long-term monitoring situations.

V. Conclusion

A passive RFID-based microfluidic-based sensor utilizing the inkjet printing fabrication method has been demonstrated for the first time. The sensor demonstrates resonant shifts of 100 MHz in cabled measurements and 30 MHz in wireless measurements over a range of different fluids. After several days of use with different fluids, the tag exhibits the same resonant frequency and reflection power in the empty and water filled states. This repeatability validates that re-usable tags can be fabricated using a low-cost process such as the inkjet process used in this work. The sensor was used to distinguish between ethanol, hexanol, and water, and is able to detect % content by volume in water/alcohol mixtures. The sensor platform built here is universal and can be extended to applications in water quality monitoring, biomedical analysis, and fluid process control.

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