All-inkjet-printed Microfluidics-based Encodable Flexible Chipless RFID Sensors

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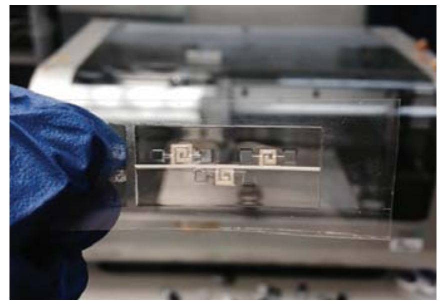
***Abstract*—This paper proposes the first-of-its-kind microfluidics-based encodable and flexible chipless RFID sensors. The prototype, including the microfluidic channels and passive RFID resonators, is manufactured cost-efficiently with sole reliance on multilayer inkjet-printing for the first time. Three microfluidics-based reconfigurable spiral resonators are used to obtain tunable "code" frequencies and encode the RFID with less than 0.5 μL of water per bit. The embedded microfluidics also facilitate sensing of various fluids (e.g. identifying different water-glycerol mixtures). The proposed chipless RFID module maintains a stable performance during bending and can be bent for radii down to at least 12 mm. The proposed encodable chipless RFID module can be used in various application spaces including healthcare monitoring, food quality sensing and liquid leakage detection.**

***Index Terms*—RFID, inkjet-printing, microfluidics, low-cost electronics, flexible electronics, fluidic sensing**

I. Introduction

Radio Frequency Identification (RFID) is a wireless data transmission and reception technique which usually comprises of an integrated circuit (IC). The cost of RFID tags highly depends on the cost of ICs, while it dominates the cost of the whole RFID systems. The ICs also need a certain power to "wake up" which imposes limitations on both passive tags and active tags. Due to their cost-effective and fully passive features, chipless RFID tags without any ICs have become an area of increased interest [1]–[4]. However, compared with an RFID containing an IC which enables encoding and signal processing, a major disadvantage of the majority of chipless RFIDs (e.g. multiple resonators-based) is that they have a fixed code that cannot be easily encoded/modified on-the-fly. Due to its capability of manipulating extremely small quantities of liquid as well as due to its compact size that allows an easy embedding into various devices, microfluidics technology has been widely used in manufacturing control, biomedical sensing, chemical assay, lab-on-chip applications and tunable electronics [5]–[7]. By introducing microfluidics to the multiresonator chipless RFID tags, a first-of-its-kind encodable low-cost fully passive RFID module can be developed, which can be used in various applications including healthcare monitoring, food quality sensing and liquid leakage detection.

Microfluidics devices as well as multiresonator-based chipless RFIDs are traditionally fabricated with photolithography and associated technologies. However, these processes are generally expensive and environmentally unfriendly. Inkjet-printing, a low-cost and rapid additive manufacture technique, is a promising alternative which has been partially used in the fabrication of chipless RFID [4] and microfluidics [6], [7]. In this paper, a low-cost and flexible microfluidics-based chipless RFID is presented, which can be entirely additively manufactured for the first time on virtually any substrate with sole reliance on multilayer inkjet-printing.



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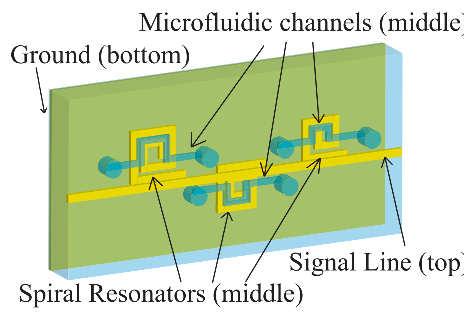

(b)

Fig. 1: (a) A photo of an all-inkjet-printed prototype with an inkjet printer in the background. (b) A 3D view of the structure.

II. Theory of operation

Multiresonators, especially spiral resonators, are commonly used in chipless RFIDs due to its simple structure and frequency-code capability [1], [3]. By embedding a microfluidic channel in the spiral's gap between adjacent turns, the capacitance of the gap can be tuned by changing the status ("filled"/"unfill") of the microfluidic channel as the relative permittivity of air and water is 1 and 80, respectively [8]. The resonant frequency would shift due to this capacitance change, enabling the encoding mechanism: the original frequency represents '0' code and shifted represents '1'. As the proposed RFID module can be toggled by filling or removing the water (or a different liquid) in the channel, one simple way to achieve that is to cover the prototype with a elastomer adhesive film and press "buttons" in Fig.2. There are numerous other possible passive or active ways to realize this functionality, such as using electrowetting to change the surface tension of liquids or using digital microfluidics to deliver liquid droplets.

The proposed proof-of-concept prototype consists of three spiral resonators and three microfluidic channels, one on the top of each spiral, as shown in Fig.1. The three spirals and the microfluidic channel are shown in Fig.4b. The signal line width is 0.7 mm and the embedded microfluidic channels feature 500 μm width and 50 μm height, which requires less than 0.5 μL to fill a whole channel. A 3-bit chipless RFID is presented in this paper, while this spiral structure is capable of a high data capacity [2]. The above mentioned multiresonator structure can be used as a chipless RFID tag by simply connecting it to two cross-polarized UWB antennas at each end. As a proof of concept of the proposed microfluidics-based encodable chipless RFID, one multiresonator structure with bandstop characteristics is prototyped.

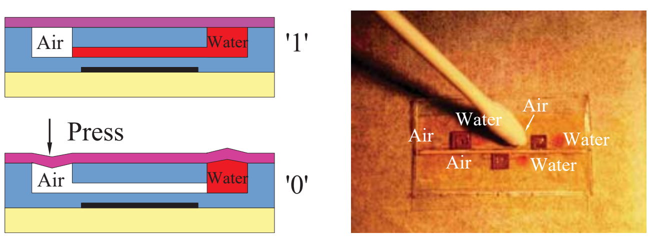

Fig. 2: One possible way to encode the chipless RFID module. (a) A side view graph of how to encode the RFID by pressing the "button". (b) A photo of a realization of the above mentioned method by covering the prototype with a Polydimethylsiloxane (PDMS) sheet and pressing the "button" with a cotton swab.

III. Fabrication

This paper introduces a low-cost all-inkjet-printed fabrication method in Fig.3 for the first time, which involves 3 different inks (silver nanoparticle ink, SU-8 ink and poly(methyl methacrylate) (PMMA) ink), utilizes the Dimatix DMP-2831 inkjet printer and a flexible and transparent polyethylene terephthalate (PET) substrate (though this process is capable for virtually any substrate). First, three spiral silver traces were inkjet-printed on PET and cured at 150 °C for 1 hour. Then, a 14-μm-thick layer of SU-8 was deposited to isolate the silver traces from the tested fluids. After cross-linking the SU-8 with UV light and heat, a 50-μm-high 500-μm-wide PMMA traces were printed as a placeholder for the designated microfluidic channel and dried at 120 °C for 1 hour. After dehydration and surface energy adjustments, another 66-μm-thick SU-8 was inkjet printed on the top to cover the PMMA traces. After cross-linking the SU-8, the prototype was hard baked at 150 °C to achieve a better mechanical resistance. The removal of PMMA was carried out by a 2-hour anisole solution bath. Finally, the signal line was printed with silver ink and was cured afterwards.

As shown in Fig.1a, all the features in the prototype, including both the electronics and microfluidics, were fab-

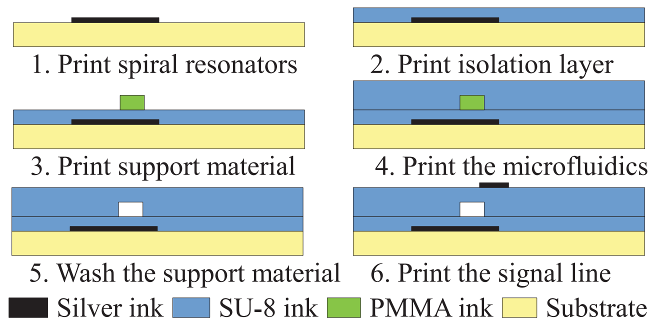

Fig. 3: Fabrication process (cross-section view).

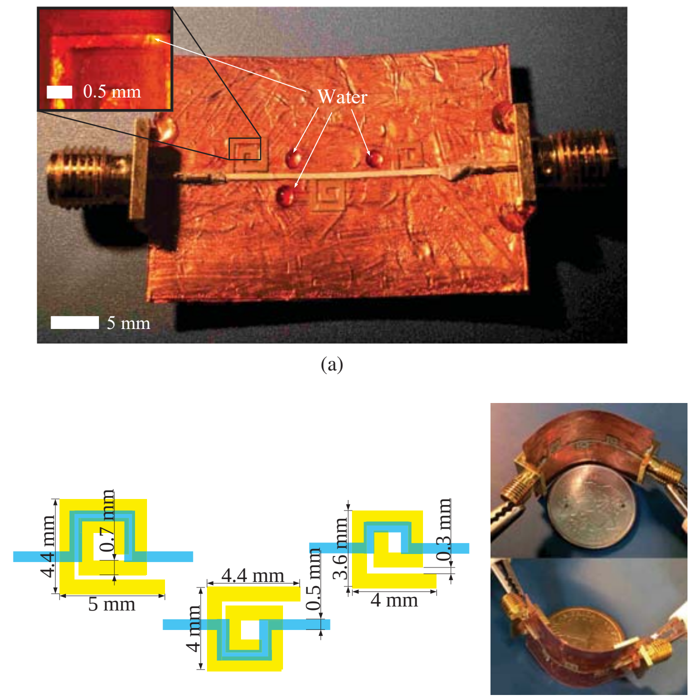

Fig. 4: (a) Photos of the fabricated prototype with water in the microfluidic channel. (b) A top view graph of middle layer (spiral resonators and microfluidic channels) with dimensions. (Blue lines stand for microfluidic channels and yellow lines stand for conductive traces.) (c) Photos of the prototype bent in two directions around a dollar (13-mm-radius) or quarter coin (12-mm-radius).

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ricated on the single platform with sole reliance on inkjet-printing for the first time. Being an additively manufacturing technique, inkjet printing is a low-cost, zero-waste, rapid and environmental friendly fabrication method. Furthermore, as inkjet-printed features are very thin (e.g. around 80 μm for proposed prototype), this process is great for fabricating flexible prototypes by simply using flexible substrate, as shown in Fig.4c. To complete the measurement setup, a ground plane made by copper tape and two SMA conntectors were attached in Fig.4a.

IV. Simulations and Measurements

The functionality of the chipless RFID module was simulated with Ansoft HFSS and was then comprehensively measured with SMA cables and a vector network analyser (VNA). Though the device is designed to work wirelessly through the use of antennas, cable measurements were chosen here to specifically evaluate the "frequency coding" functionality. Due to the ultra small channel size, fluids were fed to the channel with the help of the capillary effect: when a drop of fluid is dripped on a dry channel opening, the channel will imbibe the fluid in automatically.

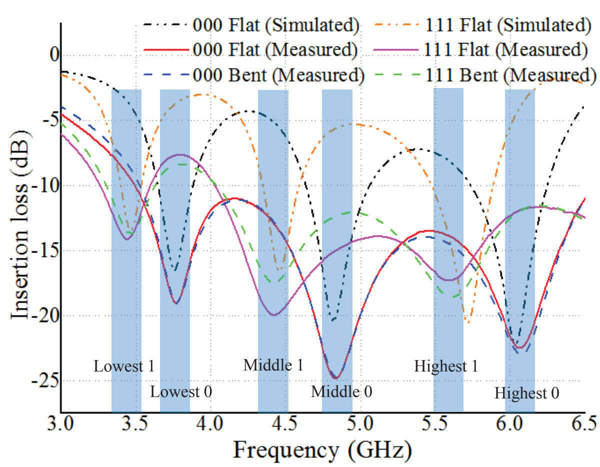


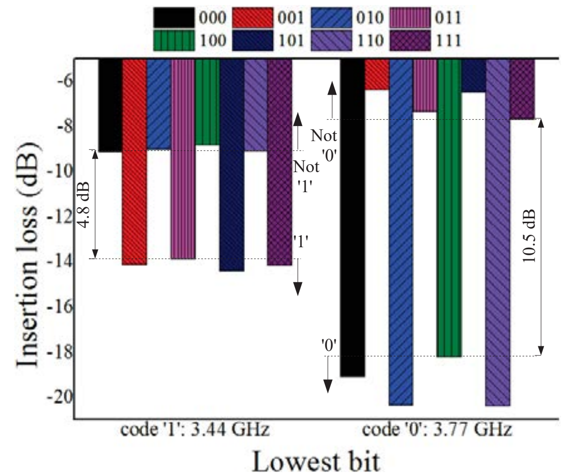
Fig. 5: Simulated and measured insertion loss values of the prototype for code "000" and "111" configurations in flat or bent for a 30 mm radius.

TABLE I: "Code" frequencies for every bit

Bit	code '1'	code '0'
Lowest bit	3.44 GHz	3.77 GHz
Middle bit	4.42 GHz	4.84 GHz
Highest bit	5.57 GHz	6.06 GHz

A. *Real-time Encoding Capability*

To test the encoding capability of the chipless RFID module, the insertion loss (S21) values were measured for all 3-bit code combinations. The measurements agree well with the simulations in the resonant frequencies as shown in Fig.5, and the six "code" frequencies of the 3-bit encoding combinations



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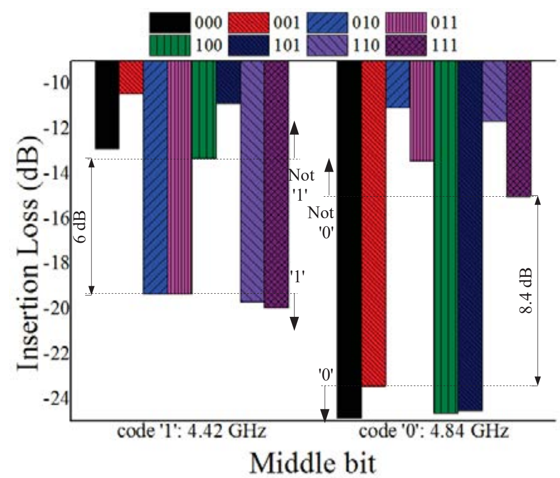

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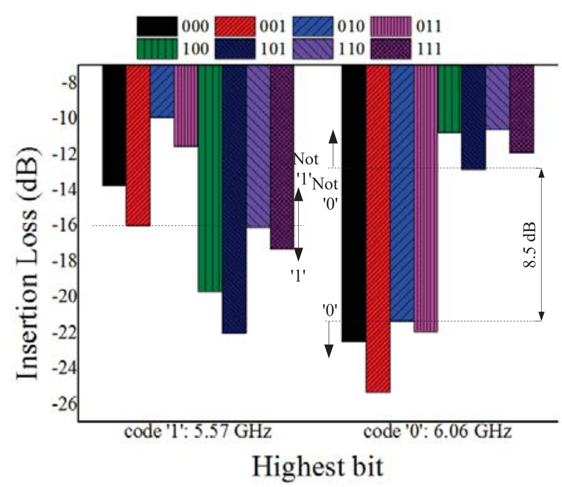

(c)

Fig. 6: Insertion loss of the prototype for various 3-bit code configurations at the coding frequencies of the (a) lowest bit, (b) middle bit and (c) highest bit.

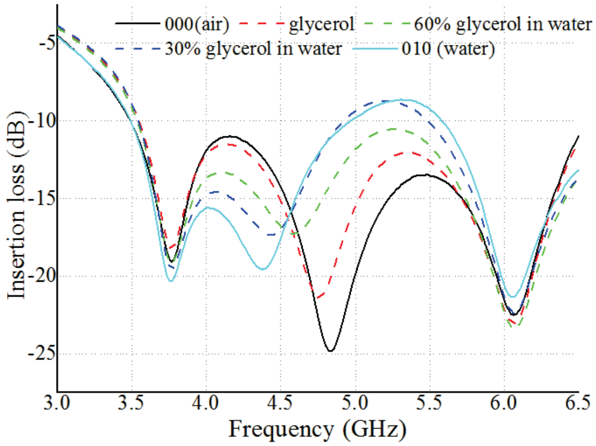

Fig. 7: Measured the insertion loss values of the prototype with the middle microfluidic channel filled by water glycerol mixtures while other two channels left empty.

can be found in Table I. In Fig.6, an at least 8.4 dB insertion loss difference between '0' and '1' can be observed at code '0' frequencies, which facilitates the bit value differentiation. This power difference is smaller at code '1' frequencies, due to the lossy nature of water (especially in higher frequency) selectively filling the microfluidic channels setting the values to '1'. The response at code '1' frequencies can be used as an add-on verification of the bit value, effectively decreasing the bit error rate (BER).

B. Sensitivity and Flexibility

Embedding microfluidics in this chipless RFID module empowers the tag to additionally conduct fluidic sensing. As permittivity values depend on the status of the fluids, such as composition and temperature [8], the resonant frequency can reflect this information and the RFID tag can send it out wirelessly. An example can be found in Fig. 7 in identifying different water-glycerol mixtures, given that the relative permittivities are about 80 for water and 41 for glycerol [8]. The sensing in this example is realized in a "0X0" configuration with the tested fluid filling only the channel on the middle bit resonator, modifying the resonant frequency of the middle resonator and keeping the other two bits unchanged at '0' frequency.

As the printed microfluidics and electrodes are extremely thin and the substrate is flexible, the fabricated prototype displays a very stable performance during bending, as shown in Fig.5. The prototype can be easily bent for radii down to at least 12 mm without breakage in Fig.4c. This flexibility enables various wearable and conformal applications.

V. Conclusion

This paper has introduced a novel flexible microfluidics-based encodable chipless RFID module composed of three microfluidics-based reconfigurable spiral resonators. The chipless RFID features an enhanced encoding capability, along with a fluidic sensing functionality. The prototype is fabricated by an all-inkjet-printing process for the first time, which is a low-cost and rapid approach with sole reliance on multilayer inkjet-printing. This chipless RFID can find application in various areas including but not limited to healthcare monitoring, food quality sensing and liquid leakage detection.

Acknowledgment

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