Wireless Printed System for Humidity Monitoring

José F. Salmerón, Andreas Albrecht, Silmi Kaffah,
Markus Becherer, Almudena Rivadeneyra
Institute for Nanoelectronics
Technical University of Munich
Munich, Germany
e-mail: jf.salmeron@tum.de, silmi.kaffah@tum.de,
andreas.albrecht@tum.de markus.becherer@tum.de,
almudena.rivadeneyra@tum.de

Paolo Lugli
Faculty of Science and Technology
Free University of Bolzano
Bolzano-Bozen, Italy
e-mail: paolo.lugli@unibz.it

***Abstract*— In this work, we present a complete wireless sensory system based on a chipless strategy in the sensor part. Instead of characterizing individually the sensor element, we show the response seen by the reader antenna through inductive coupling with respect to the detection parameter, in our case, moisture content. The wireless chipless sensor consists of an LC circuit fabricated by printed techniques on a flexible substrate. This substrate is actually the element sensitive to humidity by changes in its electrical permittivity. We show the differences in the frequency response depending on the measurement point: the variation in frequency is reduced more than 3 times when measuring at the reader antenna with 10 mm distance between elements.**

Keywords-cantennas coupling; flexible substrate; printed electronics; reader; resonance frequency.

I. INTRODUCTION

A recent trend in sensor design is to remotely access the desired information via a wireless link, facilitating the monitoring of hazardous environments or under harsh conditions. This trend is known as wireless sensors. Typical wireless sensors can be differentiated into optical sensors, surface acoustic wave sensors, intermodulation sensors and radiofrequency (RF) sensors. Among RF sensors, we can distinguish electromagnetically coupled sensors and devices working on the far or near field regions, depending on the operating frequency. In the latter case, the coupling mechanism is inductive using typically LC resonant circuits [1]-[5]. This paper focuses on the LC-type passive sensors, which offer several advantages such as simple structure, easy to integrate and inexpensive to manufacture [6]. Furthermore, the sensor is acting highly energy-efficient due to the low operating frequency and the smaller coupling distance [7]-[9]. Based on the positive characteristics, recent researchers have investigated passive LC sensors in various environmental applications: temperature [7][9], humidity [5] and pressure in the human body [10]. The core sensing system consists of an LC circuit, which is powered and interrogated remotely by a reader coil antenna. Variations in the physical or chemical conditions lead to changes in electrical properties, such as conductance or inductance, leading to a variation in the near field coupling properties. In order to obtain the resonant frequency wirelessly, an additional coil at the readout circuit is inductively coupled to the inductor of the LC circuit. The resulting frequency shift is measured by the change in the impedance of the reader coil [11]-[13]. As a consequence, parameters of interest are monitored remotely and the sensing system in the harsh environment is passively powered. Some authors have already studied the sensing capabilities of this kind of systems [13][14], demonstrating that minimal losses of the sensor is crucial to develop a wireless sensor system based on a coupled LC resonator. Moreover, the fabrication techniques employed are a critical factor because they define the performance and the cost of the sensor. In this sense, one of added value to this kind of sensors is to be manufactured by printed electronics (PE). This emerging technology can produce thin, flexible, wearable, lightweight, ultra-cost-effective, and environmentally friendly structures [15]. The combination of PE technology with wireless chipless sensors is a promising alternative to develop sensors with low-cost process and provide to this circuitry all the mentioned characteristics. In a previous work, we presented printed resonant structures on a flexible substrate for humidity detection [16]. The devices consist of a screen-printed spiral inductor working as radio frequency identification (RFID) antenna and two different inkjet-printed planar capacitive structures forming LC resonators, being the substrate the sensitive layer [16]. In the same direction, Wang et al. [17] reported a wireless humidity sensor label manufactured by screen-printing and dry-phase patterning. The sensor label includes a planar antenna, a tuning capacitor and a printed sensor-capacitor head, where changes in humidity are detected as a shift of the resonant frequency. The printed sensor head is working as a resistive-type sensor between 150 kHz and 250 kHz with a frequency shift of about 80 kHz between dry condition (10%RH) and high humidity (90% RH).

In this work, we have looked into the real operation of LC printed structures acting as humidity sensors, considering all the elements of a full wireless sensor system. In Section II the fabrication and characterization of the wireless sensor system is described. In section III, the response of the wireless sensor is studied from the reader side because this element will be in charge of collecting all the sensor

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information in any real scenario. We conclude the paper in Section IV.

II. Materials and Methods

A. Working Principle

The global idea of this work is to develop wireless and chipless sensors capable of being read out by smart devices, making use of the common frequencies and technologies already in use (i.e. Wi-Fi, Bluetooth). To better understand our global approach, let us look at the high frequency (HF) band and implemented by Near Field Communication (NFC) and some RFID protocols. At this frequency, the working principle is based on the coupling between two coil antennas, one of them acting as reader (i.e. coil inductor included in the smartphones to implement NFC) and the other one acting as tag (element that provides the reader with some desired information). Nopper et al. demonstrated that only two independent parameters of the sensor circuit, i.e. quality factor and resonance frequency, can be extracted from a wireless measurement [13]. Normally, RFID tags include a silicon chip to establish the communication and send the requested information. The input impedance of these chips is capacitive (several hundreds of pF). Therefore, in the resonant circuit, this impedance represents the C-component, while the fabricated antenna corresponds to the inductive part (L). But, in the strategy that we are going to follow, no chip is going to be included, making our sensor tag chipless. So, the capacitive part of the circuit will be defined by the designed capacitive sensor. This sensing material will change the frequency response of the tag, providing the information in an analog way. We have already proved the feasibility of this approach for humidity sensing [16]. The elements of the system (reader and wireless LC sensor) were designed to resonate at HF band with ADS software (Keysight EEsof EDA, USA) [18]. The antenna design has been focused on the optimization of the antenna quality factor because it offers a longer read range and a better reading of the sensor information [19][20].

B. Fabrication process

The selected materials were DGP-40LT-15C ink (ANP, Korea) with a solid content of 35% of silver nanoparticles dispersed in TGME (triethylene glycol monoethyl ether) for inkjetted patterns and silver conductive paste (Sigma Aldrich, USA) with a solid content higher than 75% for the screen printed ones. All the patterns were printed on a polyimide substrate with 75 µm thickness (Kapton® HN, Dupont™, Wilmington, DE, USA) taking advantage of the fact that its electrical permittivity varies with the relative humidity, as already shown in [16][21]. In order to obtain a compromise in the tag performance, the capacitive array was defined by inkjet printing to reduce the distance between consecutive fingers and, therefore, to increase the sensitivity without occupying more area whereas the coil inductor was screen printed because of its better performance with respect to the inkjetted antenna [18]. Then, the capacitive structures were defined with a DMP-2831™ Dimatix printer (Fujifilm Dimatix Inc, Santa Clara, USA) by only one printing layer. The substrate temperature was fixed at 60 °C during printing. A drop space of 40 µm was settled in the printer for 80 µm landed diameter drops followed by a drying step at 120 °C for 1 h. The inner and outer ends of the coil have been connected through a small "bridge" manufactured by ink-jet printing and attached using the adhesive epoxy EPO-TEK H20E (Epoxy Technology, Inc., Billerica, USA). A 100 Nylon threads per centimeter (T/cm) mesh were used to manufacture the screen printed patterns. The tags consisted of one printed layer with a manual screen printing machine (FLAT-DX 100 from Siebdruck-Versand, Germany). Finally the curing process took place at 120 °C for 5 min. As reader, we fabricated a coil inductor milled in Flame-Retarded class 4 (FR-4) copper clad laminate rigid substrate from Cirqoid (Latvia) with a metallization layer of 35 µm copper using a prototyping machine from Cirqoid (Latvia). A surface mount device (SMD) capacitor was soldered to resonate at 13.56 MHz. In particular, the inductance is 5.9 µH and the capacitance 31 pF.

C. Characterization

The AC electrical characterization for the different fabricated tags was performed by measuring their impedance, both magnitude and phase, using the four-wire measurement technique with a precision Impedance Analyser E4294A and an impedance probe kit (4294A1) (Agilent Tech., Santa Clara, CA, USA). The stationary humidity and temperature responses of the tags were measured in a climatic chamber VCL4006 (Vötsch Industrietechnik GmbH, Germany). The excitation voltage applied in all measurements was $V_{DC} = 0$ and $V_{AC} = 500$ mV from 5 MHz to 30 MHz. We considered this frequency range because it contains the work frequency of the RFID chip (13.56 MHz) and enough frequencies around it to perceive shifts on the resonance frequency due to variations in the relative humidity. The distance between the reader and the sensors was defined with a spacer manufactured with a 3D printer (EntresD UP Plus2, Germany). The height of this custom frame was checked with a digital calliper (DIN 862) with a resolution of 0.01 mm. Coils of sensor and reader were aligned during measurements in order to maximize the coupling factor ($M \approx 1$).

III. Results and Discussion

A. Reader characterization

Figure 1 depicts the prototypes used as reader and as wireless sensors. As can be observed, both elements present a coil inductor and a capacitor. In the case of the reader, there is only one SMD capacitor to tune the resonance frequency to the band of interest, whereas we defined an array of capacitive IDEs in the case of the wireless sensor. This array forces the sensor not only to work in the HF band but also to be the sensitive element to RH variations. The electrical permittivity of the sensing element changes with moisture content, leading to a change in the total capacitance of this array, and therefore, the resonance frequency of this wireless sensor is directly shifted.

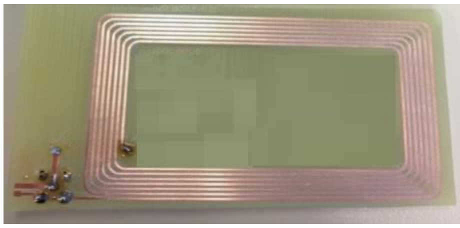
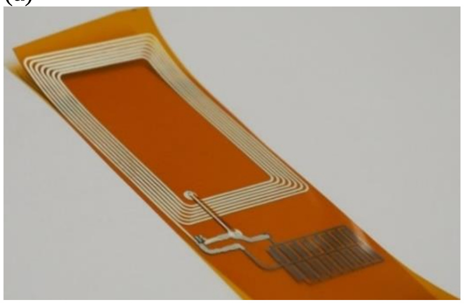

(a)

(b)

Figure 1. (a) Reader and (b) wireless sensor.

The first study carried out was the frequency response of the reader. Figure 1 shows the impedance seen by the reader when there is no tag in its vicinity and when a tag is placed at 10 mm of it. In the former case (no sensor tag in the surroundings), the reader resonates at almost 14.5 MHz, whereas when the tag is approximated, the resonance of the reader decreases 0.5 MHz. This can be explained by the fact that real and imaginary parts of reader impedance are equal at resonance condition. Thus, when a tag is in the vicinity of the reader antenna, the measured input impedance changes [13], giving as a result the shift on frequency observed in Figure 2.

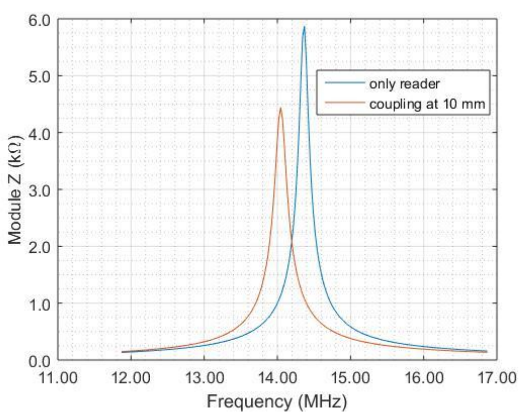


Figure 2. Module the reader and coupling between reader and wireless sensor.

It should be noticed that this relationship depends on the coupling factor, and consequently, on the distance between the two elements. Therefore, all the characterization must be done at a fixed distance. Next, we present the results for 3 different distances. It is important to clarify that in a real environment not only the reader antenna is important to define the whole systems, but also the full electronic design of the reader. One solution is to use a reader capable of detecting the resonance frequency [22][23].

B. *Wireless humidity measurements*

In our previous work, we already showed that the impedance of the coil inductor presents almost no variation with respect to humidity (less than 0.02% in the studied RH range), proving that the element responsible of the variation of the LC structure response is the capacitive element of the circuit, in our case an array of interdigitated capacitors placed in parallel in order to increase the global capacitance of the system and its sensitivity [16]. We tested the response of the sensor at 3 different distances between reader and wireless device. In particular, we placed the wireless sensor at 10, 15 and 20 mm from the reader and measured the impedance in the reader side. Due to the fact that the capacitance increases when the moisture content is higher, the resonance frequency decreases at higher RH values. This trend can be observed in the three scenarios, although the effect of the distance is clearly appreciated: At the lowest distance, the effect of the humidity level in the resonance frequency is much more noticeable than at the other two tested distances. A shift of about 150 kHz is achieved at 10 mm, whilst this shift is ten times lower when the distance is doubled.

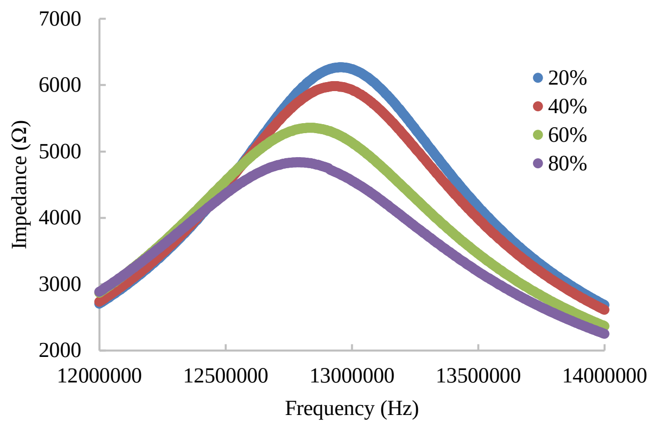
Looking at the change in the resonance frequency at the different RH levels (see figure 34), we have also noticed that the linearity of the response degrades when the distance between the two elements is too big, reducing the detection range of the system. Table 1 summarizes the variation in the resonance frequency at the RH range studied together with the calculated sensitivity for the different distances. The sensitivity is defined as follows:

$$S_{RH}(dist.) \equiv \frac{\partial freq_{T=cte}\,(RH)}{\partial\, RH} \qquad (1)$$

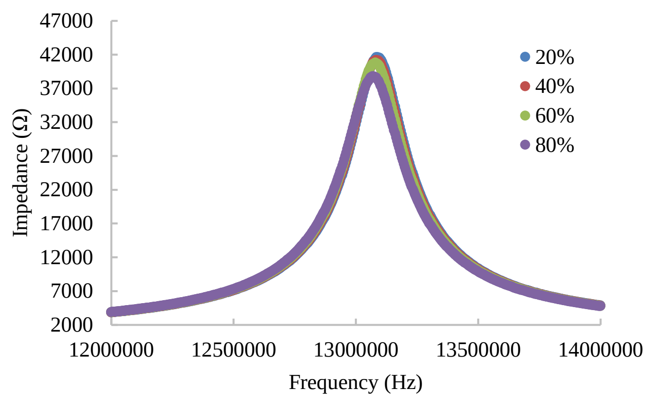
Comparing these resonance values with the one presented in [16], a reduction in the frequency shift of about 70% (~500 kHz) is observed when, instead of measuring directly the response of the wireless sensor, the measurement point is fixed at the reader side. This reduction highlights the importance of performing the characterization at the reader side when a wireless sensory system is described. This loss of sensitivity can be associated to the coupling factor (M) that is inversely related to the distance between the elements [13]. Therefore, the larger the distance between reader and sensor tags, the poorer their coupling factor and, thus, the lower the sensitivity of the wireless sensor.

TABLE I. RESONANCE FREQUENCY OF THE READER WHILE COUPLING THE WIRELESS SENSOR AT THE MINIMUM (20%) AND MAXIMUM (80%) RH LEVEL TESTED FOR DIFFERENT DISTANCES.

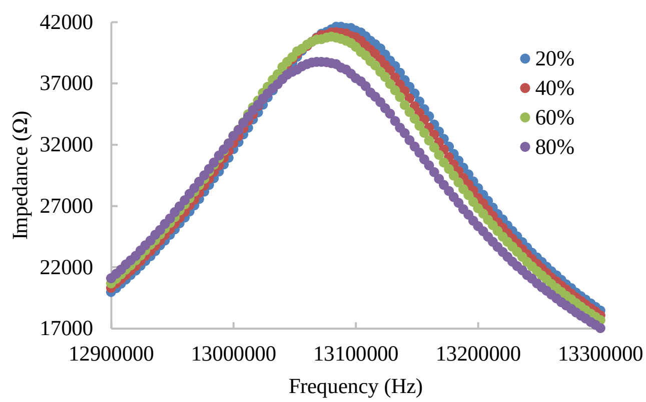
Distance (mm)	Freq. Change (kHz)	Sensitivity (Hz/%RH)
10	148	$-2.60\cdot10^3$
15	21	$-0.30\cdot10^3$
20	14	$-0.20\cdot10^3$



(a)



(b)



(c)

Figure 3. Impedance module of the reader while coupling the wireless sensor vs. over frequency at 30 ºC for different RH values at a distance of (a) 10 mm; (b) 15 mm; (c) zoom of (b).

IV. Conclusions

In this work, we present the characterization of a wireless chipless system focusing our interest on the reader side. Normally, this kind of systems is described by showing only the frequency response of the sensor to the magnitude of interest but it is forgotten what happens in a real environment where a reader element needs to extract the sensor information. For this reason, we have shown the coupling characteristics of the chipless sensory system at the reader side, varying the distance between the two antennas: reader and sensor one. To do that, a wireless chipless device sensitive to moisture content have been fabricated by printed techniques on a flexible substrate and placed in the vicinity of a reader in FR-4 technology, showing how important is the influence of the distance between the devices is critical for the proper and ubiquitous use of the system. In particular, a sensitivity of -2.6 kHz/%RH is observed at 10 mm distance while this value decreases more than 10 times when the separation between the reader and the wireless sensor is doubled.

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