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Compact readout system for chipless passive LC tags and its application for humidity monitoring

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ABSTRACT

The development of a contactless readout system for High Frequency (HF) tags and its application to relative humidity monitoring is presented. The system consists of a Colpitts oscillator circuit whose frequency response is determined by a built-in logic counter of a microcontroller unit. The novel readout strategy is based on the frequency response change due to the inductive coupling between the coil of the Colpitts oscillator and the load impedance of a parallel LC resonator tag, as a result of the variation of the humidity sensing capacitor. The frequency is monitored with a low cost microcontroller, resulting in a simple readout circuit. This passive LC tag has been directly screen-printed on a humidity-sensitive flexible substrate. The readout circuit experimental uncertainty as frequency meter was 4 kHz in the HF band. A linear temperature drift of (-1.52 ± 0.17) kHz/°C was obtained, which can be used to apply thermal compensation if required. The readout system has been validated as a proof of concept for humidity measurement, obtaining a significant change of about 260 kHz in the resonance frequency of the Colpitts oscillator when relative humidity varies from 10% to 90%, with a maximum uncertainty of ±3% (±2 SD). Therefore, the proposed readout system stands as a compact, low-cost, contactless solution for chipless HF tags that avoids the use of bulky and costly equipment for the analog reading of wireless passive LC sensors.

1. Introduction

The compatibility of Printed Electronics (PE) and sensors with flexible substrates has enabled the development of sensor systems in attractive form factors than can be deployed, for instance, into pharmaceutical or intelligent food packaging applications [1–3]. Among the different parameters of interest, the monitoring and control of humidity has been employed in different industrial applications such as smart packaging of goods and food to ensure quality preservation [4–7] or humidity surveillance within construction structures [8,9] among others. LC wireless passive sensors are a suitable solution in applications where powered and wired sensors are not possible [10–13].

The transduction mechanism of humidity capacitive sensors requires the use of materials whose electrical permittivity changes accordingly to the environmental relative humidity [14]. Several strategies have been followed to achieve this sensing capability, such as the deposition of a sensing layer over capacitive patterns [15–17] or the use of humidity-sensitive substrates [18–20]. For instance, a paper-based moisture sensor that uses the hygroscopic character of paper to measure patterns and rate of respiration was reported [21]. The most common planar capacitor design is the interdigitated electrode structure (IDE) [7,10,14–16], although others have been proposed such as a serpentine electrode structure (SRE) [18,22].

The inclusion of sensing capabilities into Radiofrequency Identification (RFID) tags brings added value to this contactless, non-line-of-sight identification and data transmission technology [23,24]. When the RFID tag is used as an electromagnetic sensor, different changes in the analog response of the tag have been associated to a variation of the sensed magnitude. This approach has been used to develop humidity sensors in flexible High Frequency (HF) tags by exploiting the RFID tag resonance frequency shift measurement. Polyimide, a material sensitive to moisture, was employed as substrate of a printed inductor and an interdigitated capacitor (using screen and inkjet printing techniques) to form an LC res-

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onator for moisture detection [18]. The same operating principle was used for Ultra-High Frequency (UHF) tags [25]. Moreover, a passive RFID gas sensor with a resonant antenna coated with a gas-sensing film and an IC memory chip was presented [26]. A chipless RFID tag consisting of two inkjet-printed planar LC resonators was developed for humidity detection utilizing paper substrate as sensing material [20]. Another example to measure threshold humidity in a UHF tag by changing the antenna input impedance was proposed [27]. Very recently, a flexible RFID tag for humidity and temperature sensing has been proposed [28]. In this chipless tag, the variations of the monitored magnitudes are associated to changes in the measured level of the backscattered power. Mraović et al. proposed a screen-printed capacitive humidity sensor integrated in a UHF tag and fabricated on recycled paper and cardboard for smart packaging applications [29]. Other examples of flexible RFID tags as electromagnetic sensors can be found in literature for moisture sensing [30–32]. There are some other high stable quartz methods using capacitive sensor with low value (a few pF) also for humidity measurement, which explain how to compensate environment effect [33–36].

Among the different solutions, chipless approach is a very promising one to actually achieve a cost-effective transfer of fully printed sensing tags to industrial manufacturing processes [20,37]. Nevertheless, costly and bulky equipment such as impedance analyzers [4,8,18], spectrum analyzers [38] or vector network analyzers (VNAs) [20,28] are mostly required to read the sensed magnitude based on analog measurements such as impedance or frequency spectra. Zhang et al. [39] developed an ad-hoc system to measure the relative humidity using a resonant LC tag, monitoring the real part of the readout coil impedance.

To overcome this shortcoming, here we present the development of a low-cost, portable, non-contact LC readout circuit for sensing-enabled HF RFID tags and its application to relative humidity monitoring. The reader circuit is based on capacitive sensing by means of a Colpitts oscillator. The ambient humidity modifies the oscillation frequency of the Colpitts by the capacitive load change of an inductively coupled humidity-sensitive LC tag. The frequency of the oscillator is registered by a microcontroller. The main advantage of this technique is the very simple electronic readout circuit as it will be shown later. The LC tag consists of a screen-printed chipless passive system based on a parallel LC resonator structure. In the literature, there are a few examples of capacitive sensors with Colpitts oscillator for heartbeat, respiration activity and position monitoring [40–45]. Works have been also published on inductively coupled passive resonance sensors [13,39,46–49].

2. Materials and methods

The readout circuit was fabricated on FR4 substrate with 35 μm thick cooper using a mechanical milling machine model ProtoMat® S100 (LPKF Laser & Electronics AG, Garbsen, Germany). The complete LC tag (loop inductor and capacitor) was screen-printed using a Serfix III screen printing machine (Seglevint SL, Barcelona, Spain) on 75 μm thick flexible Polyimide Kapton® HN substrate (DuPont™, Wilmington, DE, USA). The screen mesh used for printing consisted of an aluminum rectangular structure of 50 cm × 35 cm with mesh density of 120 Nylon threads per centimeter (T/cm) allowing a minimum width pattern of 300 μm. The patterns were printed using the conductive silver-based ink SunTronic CRSN 2442 (Sun Chemical, New Jersey, USA). After printing, a thermal sintering process was carried out at 120 °C during 20 min in a convection air oven Venticell VC55 (MMM Medcenter Einrichtungen GmbH, Munich, Germany). Finally, a bridge line was attached to close the circuit using the conductive resin Epoxy EPO-TEK® H20E (Epoxy Technology Inc., Billerica, USA). The Epoxy resin was cured in the oven at 150 °C for 15 min.

Physical dimensions of the LC tag components were optimized via numerical simulation using Advanced Design System (ADS) simulator (Keysight Technologies, Santa Clara, CA, USA) and COMSOL Multiphysics® (Comsol Inc., Burlington, MA, USA). The design goal was to achieve the minimum possible dimensions accounting for the limitations of the printed technology. Impedance frequency characterization of the reader and tag systems and their components (inductors and capacitors) separately was carried out using an Agilent 4294 A Precision Impedance Analyzer and a 42941 A impedance probe kit (Keysight Technologies, Santa Clara, CA, USA). Readout system calibration as frequency meter was performed with an Infiniium MSO9104 A oscilloscope (Keysight Technologies, CA, USA).

The stationary thermal drift measurements of the readout system and the humidity calibration of the full system (LC tag and readout system) were controlled in a climatic chamber VCL4006 (Vötsch Industryetedhnik, Germany) along with an external compressed air dryer from the same manufacturer to extend relative humidity range from 10% to 98% within a temperature range from 10 to 95 °C. According to the technical data provided by the manufacturer, this climate chamber model has a humidity deviation in time from ±1 to ±3% and a temperature deviation in time from ±0.3 to ±0.5 °C relative to the set value.

3. Detection principle of the readout circuit

The resonance frequency of a Colpitts oscillator circuit, f_{osc}, is given by [50]:

$$f_{osc} = \frac{1}{2\pi\sqrt{L_{osc}C_{osc}}} \tag{1}$$

where L_{osc} is the total inductance of the oscillator coil and C_{osc} is the total capacitance of the circuit in parallel to the oscillator coil. The readout technique proposed here is based on the inductive coupling between the Colpitts oscillator coil and the printed LC tag coil, which contains a sensing-enabled capacitance (see Fig. 1a). As we will show below, a contactless way to measure capacitances is used in this study. It must be taken into consideration that the coupled system must operate in the inductive region of the LC tag impedance to ensure an inductive coupling.

When both coils are inductively coupled, it can be modelled as a transformer with air core. Therefore, the secondary impedance can be determined by measuring the impedance at the primary winding. If the transformer is considered as ideal, the contribution to the capacitance at the primary winding (in the readout circuit), C_{load}, due to the tag capacitor, C_{tag} is given by:

$$C_{load} = \left(\frac{N_S}{N_P}\right)^2 C_{tag}, \tag{2}$$

where N_S and N_P represent the turn number of secondary and primary windings respectively of the transformer model (Fig. 1b). This capacitive load is in parallel with the capacitance of the uncoupled Colpitts oscillator, C_{osc}. Therefore, total loaded oscillator capacitance, C'_{osc} when the LC tag is inductively coupled can be approximately written as:

$$C'_{osc} = C_{osc} + C_{load} = C_{osc} + \left(\frac{N_{tag}}{N_{osc}}\right)^2 C_{tag}. \tag{3}$$

To account for the magnetic flux losses (coupling factor less than unity) [52], we consider that the actual load capacitance will be a fraction of C_{load}, in any case, keeping the additive dependence with C_{tag} shown in Eq. (3). Because of the coupling, this increment of oscillator capacitance ($C'_{osc} > C_{osc}$) will cause a reduction of the