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Novel undercoupled radio-frequency (RF) resonant sensor for gaseous ethanol and interferents detection

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ABSTRACT

This paper introduces a novel undercoupled RF resonant sensor platform that enables gaseous phase chemical detection for passive sensor-embedded RF devices and RFIDs. The resonant sensor is implemented with an interdigital chemi-capacitor and a transmission-line inductor, thus only requiring a simple two-layer fabrication process. Its superior sensitivity at RF frequencies arises from the benefits of response amplification near resonance, as well as the shorter wavelength at radio-frequencies. Furthermore, the interdigital capacitor allows polymeric sensing materials to be directly deposited atop, thereby improving fabrication repeatability. The sensor prototypes are loaded with three different polymeric sensing materials – OV225, OV275, and SC201(SXFA) – aiming to detect certain pre-perspiratory transdermal biomarkers including gaseous phase ethanol, methanol, and benzene. Their respective responses are recorded in terms of three distinctive RF parameters – resonant frequency shift (Δf_0), response amplitude change (ΔS_{11}), and response delay change (ΔGD_{11}) – from which the sensitivities of these sensors are determined, and their selectivities with respect to the sample gas analytes are subsequently characterized. Finally, evaluation of the response signatures of the polymeric sensing materials to each gas analyte enables future development of sensor array systems that can distinguish desired analytes from unwanted interferents.

1. Introduction

Wireless sensor technology has a large market nowadays and is being employed in a wide range of applications. This paper presents a highly sensitive novel radio-frequency (RF) based gaseous chemical sensor for wireless applications. The sensor implements an RF resonator consisting of a coplanar waveguide (CPW) transmission line inductor and an interdigital chemi-capacitor coated with polymeric sensing materials for gaseous chemical sensing applications. The resonant sensor responds to chemical stimulation by changing the response amplitude (S_{11}) and delay (GroupDelay$_{11}$, or GD$_{11}$) of an incoming RF signal pulse. The reflected pulse carries the sensor readout information, and can be transmitted along with other information (i.e. identification, time stamp, and etc.) back to the interrogator; this readout method is also capable of eliminating the need for analog-digital converter (ADC) on the sensor unit [1].

The concept of resonant sensor is has been illustrated in [2], and patented in [3,4], with [3] specifying the interrogation method of frequency-sweeping and [4] indicating the use of reflection amplitude and phase of the resonant sensor response to achieve passive sensing capabilities against ambient chemicals or analytes (e.g., volatile organic compounds, VOCs). Other resonant sensor designs were reported in [5,6], which also use resonant sensor configurations for active sensing applications. General Electric [7] has recently developed a sensor-embedded RFID where the antenna patch is entirely coated with a polymeric sensing material; upon exposure to gaseous analytes, the antenna cross-section subsequently changes, thereby proportionally varying the response amplitude of the sensor. Based on the same concept of resonant sensors, various 3-D resonant structures are deployed for chemical and physical sensing purposes, such as mechanical resonant vibrometer [8], high precision resonant airflow sensor [9], aqueous chemical concentration sensor [10,11], in-line gaseous chemical concentration sensor [12] and biosensors [13]. However, as far as a compact, planar resonant sensor is concerned, the majority of the designs in previous publications deploy a parallel-plate capacitor as the sensor backbone for sensing performance, at the cost of increased

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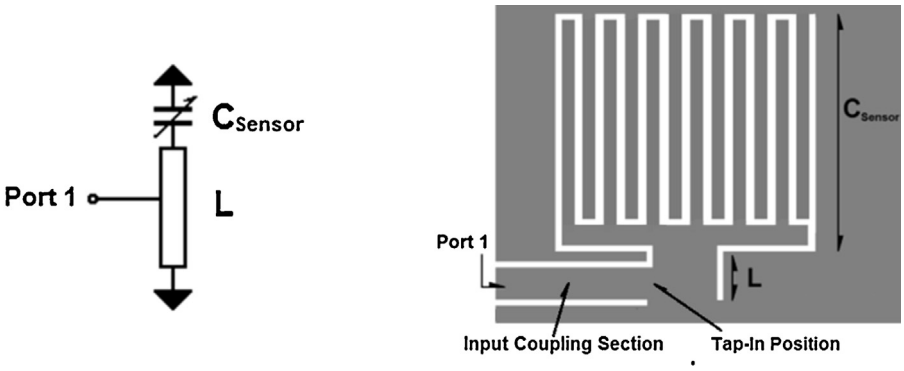

Fig. 1. Combline LC-based RF resonant sensor model (left) and its CPW implementation (right).

difficulty and complexity in polymeric sensing material deposition. Moreover, the measurement of GD_{11}, which is more sensitive to the shift in resonant frequency (f_0) than S_{11}, was never considered as a readout pathway by any articles; those designs implementing antenna cross-section variation are furthermore prone to wireless channel interference and attenuation, thus compromising the readout accuracy. In summary, none of these sensor designs are optimized for RF operations.

The novel RF resonant sensor design proposed in this paper utilizes the complete set of dispersive characteristics of an RF resonant device, incorporating the sensor information in both the amplitude and the delay of the signal pulses. This way, sensor readings can be interrogated not only over a passive communication platform as proposed in [4], but also as an integrated part of an RFID signature response from pulse dispersion-based passive chipless RFIDs proposed in [14,15]. Most importantly, since the sensor design is of high simplicity and free of ADC, it is highly suitable for flexible devices for wearable epidermal sensing applications and novel RF-resonant sensor array integration demonstrated in [16] to achieve the smallest possible sensor size and highest possible fabrication simplicity for low-cost, mass-producible, and disposable applications. Such advantages are even more evident when comparing our novel sensor design to various ultra-sensitive capacitive sensor and sensor system designs, such as the CMOS zeptofarad capacitive sensor [17], the femtofarad microfluidic sensor [18], and the quartz crystal-based mechanical resonant sensor [19,20].

The sensor prototypes are coated with selected polymeric sensing materials, and exposed to various gas analytes under a controlled environment to fully characterize their performance. The results will be used in future research to not only design sensors for specific target analytes, but also enable sensor arrays to detect the presence of multiple analytes simultaneously. In this paper, epidermal ethanol biomarker [21,22] has been employed as the example target analyte for a transdermal alcohol sensing application [23], with two common epidermal interferents, methanol and benzene, included for sensor selectivity characterization as outlined in [23]. Some of the sensor and sensor system designs in the literature reviewed previously are also suitable for the detection of these gaseous chemical compounds, and will be used as standards for the performance comparisons.

2. Theory and design

Resonant sensors are known to yield a much higher sensitivity than static sensors, as the sensor response near resonance is drastically affected by the shift in resonant frequency (f_0) of the sensor [24]. Fig. 1 illustrates the circuit model and the coplanar waveguide (CPW) realization of an inductor–capacitor (LC) resonant sensor implemented with interdigital chemi-capacitive capacitor as the sensing element. The input coupling section, indicated as port 1 in the figure, is where the high frequency signals are delivered into the resonant sensor, and where the reflected high frequency signals are captured for sensor readout.

The resonant sensor captures changes in environmental parameters of interest through capacitance variations arising from changes in dielectric constants (ε_r) and volume of the functional polymer. Even though parallel-plate chemi-capacitors are commonly known to yield better performance as sensing elements, the performance of interdigital chemi-capacitors is in fact highly dependent on the operation frequency. As illustrated on the left side of Fig. 2, at DC and low-frequency AC, a sizeable portion of the fringing electric field passes through the substrate; this portion of the field would not see any changes in electrical and physical properties of the functional polymer, and therefore, it would merely be a 'dead-weight' that would degrade the sensing performance. However, this drawback becomes increasingly negligible for higher operation frequencies.

As illustrated on the right side of Fig. 2, the electric field is highly concentrated at the conductor surface at RF, as the wavelength of the propagating electromagnetic (EM) wave approaches the dimension of the thin-film interdigital chemi-capacitor [24], thus allowing significantly more field lines to pass through the polymeric sensing material. Based on the Ansoft High-Frequency Structure Simulator (HFSS) simulation results at the selected operation frequency of 6.7 GHz, more than 95% of the electric field is confined within 5um above and below the conductor surface between the capacitor fingers of the interdigital capacitor. Accompanied by the relative ease of polymer deposition and simple fabrication, the interdigital chemi-capacitor is a more preferred design choice for RF resonant sensor applications.

Traditionally, the changes in sensor capacitance (ΔC_{Sensor}) are relatively small; in view of the resonant frequency, $f_0 = 1/(2\pi(L{\cdot}C_{Sensor})^{0.5})$, a small ΔC_{Sensor} would translate into an even smaller Δf_0. However, as illustrated in Fig. 3, for a resonant sensor being sampled at an arbitrary frequency near f_0, the response amplitude (S_{11}) and the response delay ($GroupDelay_{11}$, or GD_{11}) both see drastic changes under a relatively small Δf_0, or small

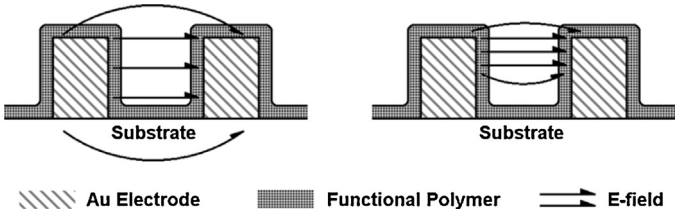

Fig. 2. Electric field distribution around the polymer-coated interdigital chemi-capacitor electrodes at low frequencies (left) and RF frequencies (right).