Impedance Phlebography Based Pulse Sensing Using Inductively-Coupled Inkjet-Printed WRAP Sensor

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***Abstract*—While mobile health (mHealth) provides tremendous opportunity to monitor patient health, continuous monitoring of various physiological data can be enhanced with body-worn sensors. In this paper, we demonstrate impedance phlebography (IPG) based pulse sensing using inductively coupled Wireless Resistive Analog Passive (WRAP) sensors that are prototyped on paper using inkjet printing (IJP) technique. The prototyped sensors were flexible and easy to attach to the body. The wireless scanning was performed at 13.56 MHz utilizing inductive coupling technique. The sensor composes of only a planar spiral coil (PSC), a tuning capacitor, and a MOSFET transducer. The IPG data was collected from IJP printed pads (5mmX10mm). The envelop of the captured signals correspond to the pulse and verified with a pulse oximeter. The computed pulse rate was 72 bpm with a 5-sec. capture window, an acceptable error of 3.5%. The prototype showed the possibility to develop WRAP sensors with IJP technique for various physiological signals that might further enhance mHealth capabilities for improved healthcare.**

I. Introduction

Mobile Health (mHealth) technology has enabled a revolution in computerized health interventions, with an estimated 200 million smart phone users in the USA. However, current smart phones have limited sensors, leading to a very limited capture modality for physiological signal monitoring with smart phones. But, traditional body-worn sensors are a major burden with lifestyle compatibility, indicating that simplified wearing experience and eliminating battery may yield better results [1]. Even though high energy density miniature batteries, newer energy harvesting techniques, and contactless remote sensing are promising, fully-passive wirelessly powered sensors present significant opportunity as they can seamlessly collect physiological data. These body-worn electronic battery-less fully-passive sensors can collect multiple physiological data from patients at real-life settings.

We have developed and reported Wireless Resistive Analog Passive (WRAP) sensors that can sense bioelectric potential [2]. In this paper, we present an application of this sensor for pulse rate monitoring with body-worn WRAP sensors, which were prototyped utilizing ink-jet printing (IJP) technique.

II. Theory

A simplified schematic of the scanner (Tx) and a WRAP sensor circuits (Rx) are shown in Fig. 1. We have utilized ISM 13.56 MHz as the carrier frequency. The transmitter contains a carrier signal generator. The L_p and C_p constitute a Tx tank circuit and impedance matched with C_1. The sensor tank circuit consists of L_s, C_s, and the resistive element ($R_{Source\text{-}Drain}$) of source-to-drain of the MOSFET (Q_1). The input voltage at the gate of the Q_1 alters $R_{Source\text{-}Drain}$ at the WRAP sensor that correlates change of Q of the sensor.

Impedance phlebography (IPG) is a non-invasive technique to measure small changes in electrical resistance that typically reflects blood volume changes [3]. In this technique, a small current is passed through two electrodes (Pad 1 & 4), while a voltage drop is monitored by another set of electrodes (Pad 2 & 3). If these pads are attached to the body such that there is a blood vessel (e.g. artery) underneath the skin, the impedance will change when the blood flows. We have attached these pads at the wrist to capture pulse rate data with the WRAP sensor.

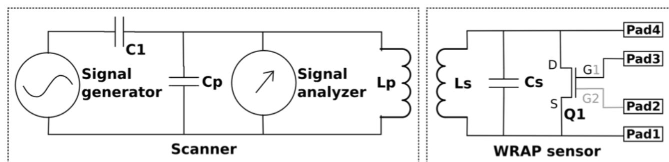

Fig. 1. Simplified schematic for WRAP scanner and sensor circuits for impedance phlebography based measurements. The tuning capacitors (*Cp* and *Cs*) are selected to match at the desired resonance frequency. The items shown in grey are relevant only for dual-channel MOSFET case, and not used for single channel MOSFET.

III. Prototyping and Experimental Setup

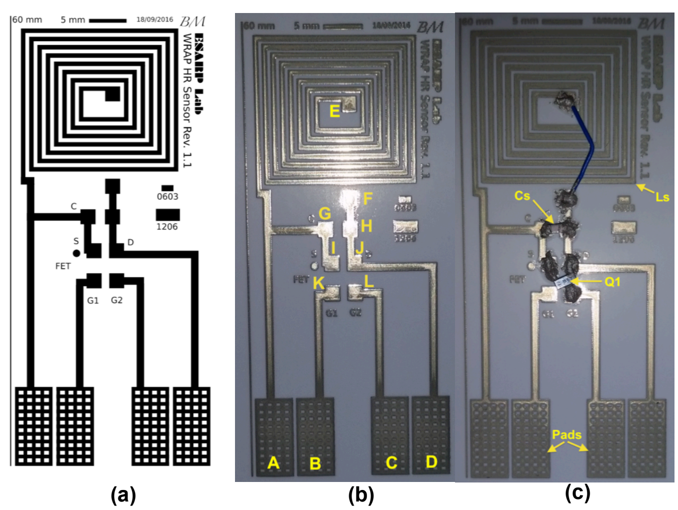

Fig. 2. (a) Designed layout of the impedance phlebography WRAP sensor. (b) A photograph of prototyped WRAP sensor on a paper using silver ink with IJP technique. (c) A photograph of a populated WRAP sensor used for functional testing.

To design the WRAP sensor antenna, we have utilized our previously describe iterative method for optimal printed spiral coil (PSC) design technique [4]. As the resistivity of silver is higher than that of copper (used in traditional PCB), this factor needs to be carefully considered for design. The antenna design

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parameter utilized this utilizing following parameters: permittivity of substrate photographic paper (ε_r) = 3.46 [5], trace thickness (t_t) = 500 nm, substrate thickness (t_s) = 200 µm, surface resistivity of printed silver ink ($R_{\square}$) = 20 mΩ/□ [6], desired carrier frequency (f_c) = 13.56 MHz, coupling factor (k) = 0.06, and empirical coefficients (α,β) = (0.9,0.1).

While the Fig. 1 shows the possibility of two gates (dual gate MOSFET), in this prototyping, we have used a single gate MOSFET whose gate terminal was connected to Pad 3. The layout design, an ink-jet fabricated prototype, and a populated prototype are shown in Fig. 2.

Fig. 3 shows the experimental setup of a wrist attached WRAP sensor with pads approximately on the artery. The scanner board is held above the WRAP sensor manually. The scanner is connected to a signal generator and an oscilloscope. The ground truth is collected using a pulse oximeter device (Accu-rate, Finger Pulse Oximeter, Model: CMS50D).

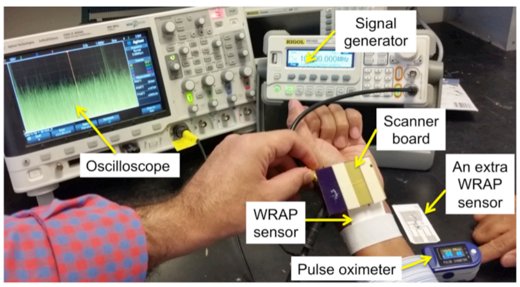

Fig. 3. Experimental setup of a WRAP sensor attached to the wrist while being scanned, showing an extra WRAP sensor.

IV. Results

The developed prototypes with single-coat print of silver ink with IJP leads to thin films silver traces of ~500 nm thickness [6]. The resistances of printed silver traces as measured between various pads (as indicated in Fig. 2b) are given in Table I.

Table I: Measured resistances of printed traces among pads

Pads	R(Ω)	Pads	R(Ω)	Pads	R(Ω)	Pads	R(Ω)
A-E	16.1	G-E	15.1	D-J	0.8	G-I	0.1
A-G	0.7	B-K	0.5	D-H	0.8	H-F	0.1
A-I	0.8	C-L	0.5	D-F	0.9	H-J	0.1

During the test, first the frequency of resonance is determined, as it might change due to parasitic resistances (e.g. from silver epoxy) and capacitances (e.g. from SMD to trace). Using frequency sweep method, Fig. 4 shows that the resonance was found to be around 13 MHz, very close to the designed frequency. The signal generator is then fixed at the resonance frequency, and data was collected for a 5-second window using the oscilloscope (at normal mode). Fig. 4 also shows the positive envelop of the captured signal at the oscilloscope. The captured data was stored in CSV file format, and then later was analyzed with a Matlab script to plot the data. The raw data in Matlab was first filtered with a second order Butterworth filter (0.05 nominal cutoff frequency).

A representative data after filtering is shown in Fig. 5, which clearly shows the peaks (and valleys) of the collected signal. The time period between consecutive peaks (or valleys) represent pulse duration, which can be utilized to compute pulse rate. For 10 trials (Fig. 5), the average HR captured by the WRAP sensor was 72 bpm, whereas the measurement from ground truth (pulse oxymetry finger device) was 74.6 bpm. The error of 3.5% is acceptable, specially considering that the measurements were captured for 5 seconds, leading to truncation issues that lower the computed bpm. Lesser error can be expected with longer data capture window.

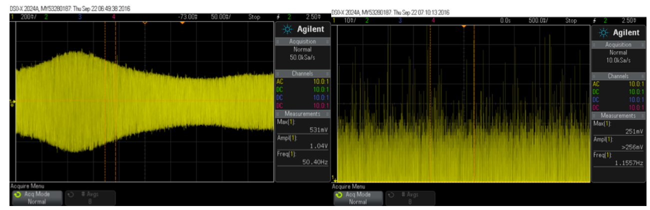

Fig. 4. (Left) Snapshot of signal envelope recorded with the oscilloscope signal analyzer. (Right) Snapshot of signal envelope recorded with the oscilloscope signal analyzer.

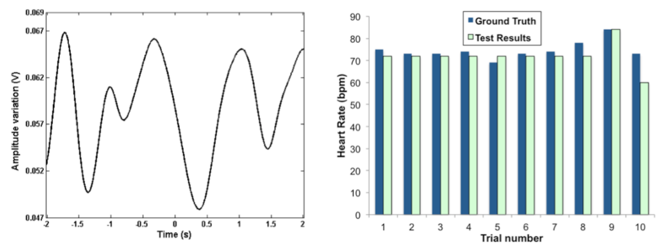

Fig. 5. (Left) Processed output of data collected by the oscilloscope after low-pass filtering using Matlab software. (Right) Test results of the WRAP sensor compared to Ground Truth data.

V. Conclusion

This work shows pulse rate capturing using IPG technique using the body-worn WRAP sensors fabricated with IJP technology on paper substrate for mHealth applications.

Acknowledgement

The antenna design was conducted by Babak Noroozi, a graduate student of EECE, based on his research work [4].

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