Single Chip Interrogation System for A Smart Shoe Wireless Transponder

Shahrzad Sheibani, Meisam Roshan, Haiying Huang, Bhaskar Banerjee, Rashaunda Henderson

Abstract— **The objective of this paper is to design a wireless transponder for antenna-based sensors that can be used to simultaneously measure shear and pressure forces for diabetic foot diagnosis. The transponder will be placed on the top surface of a shoe and consists of sensor antennas and an identification system that transmits information to a receiver by modulating the signal reflected by the antennas sensor in the insole. The identification system includes an energy harvester, a crystal oscillator and a passive mixer. A single chip interrogation circuit has been designed in IBM130 nm CMOS technology to reduce size. The identification system including bond pads has a size of 1.2mm × 0.8mm.**

I. INTRODUCTION

Fast growing wireless transceiver technology makes it a suitable candidate for biomedical applications. These wireless transceivers are able to transmit and process different types of bio-signals such as body temperature, heart rate, blood glucose and blood pressure using different wireless protocols like ZigBee, Bluetooth and RFID. However the main challenges are to minimize power consumption and size of the wireless transceiver in order to place a high density of sensor nodes on the patient or even implant in the human body.

Foot ulcers, caused by foot pressure and shear, are one of the important issues for diabetic patients. Therefore monitoring pressure and shear is recommended to prevent the onset of foot ulcers. One way of monitoring is to implement the sensors in the insoles of the shoes so as to measure pressure and shear simultaneously. Therefore, there is a need for an integrated system to acquire and transfer measured shear and pressure data. There are several challenges facing these systems such as high sensor density, minimum power consumption and sensor wiring.

Different studies have been conducted to resolve the above issues. A variety of commercial products like the F-Scan® System (Tekscan, Inc., Boston, MA, USA) [1] and the Pedar® System (Novel GmbH, Germany) [2] are available in the market for pressure sensing. Unfortunately, these systems use physical wires to connect sensors and the data acquisition systems make them uncomfortable to use. Ref. [3] and [4] presented a wearable and wireless in-shoe system using a Bluetooth module. However, both systems used discrete boards for the insole sensors and the wireless transceiver. In addition both systems require a battery source to power them up, which limits the size and operational time of the system.

S. Sheibani, M. Roshan, B. Banerjee and R. Henderson are with The University of Texas at Dallas, Richardson, TX 75080. (email: sxs061600@utdallas.edu; phone: 972-883-6454).

H. Huang is with The University of Texas at Arlington, Arlington, TX, 76019.

Mohammad and Huang developed two microstrip-based antenna sensors to measure shear and pressure [5,6]. A microstrip patch antenna measures the shear while the pressure sensors operate based on the principle of a microstrip loop antenna. The shear or pressure applied on the antenna sensors causes the antenna's resonant frequency to shift, thus the pressure and shear can be measured from changes in the resonant frequency. These two sensors can be combined vertically to measure shear and pressure simultaneously [7]. One advantage of planar antenna sensors is that they only need simple circuitry for the wireless interrogation system. Therefore a high sensor density can be implemented in a shoe. The primary goal of this paper is to integrate the implementation of the antenna sensor circuit onto a single CMOS IC to reduce the size and overall system cost. In Section II, the principle of the wireless interrogation is presented. In Section III, the energy harvester and wireless transponder are introduced. Section IV describes the measurement and results. Section V describes the conclusion.

II. PROPOSED WIRELESS INTERROGATION

To wirelessly interrogate an antenna sensor that is embedded in the insole of a shoe, Huang proposed the wireless transponder shown in Fig. 1. The wireless transponder consists of a sensor identification system and two antennas for receiving (Rx) the interrogation signal and transmitting (Tx) the sensing signal. Two frequency components are received by the Rx antenna; one for powering the identification system and one for interrogating the antenna sensor. The diplexer directs the power signal f_p to a radio frequency (RF) energy harvester, which in turn powers a crystal oscillator to generate the modulation signal f_m. The interrogation signal f_i is routed toward the antenna sensor through a circulator, reflected by the antenna sensor, and routed to the frequency mixer, which mixes the signal reflected by the antenna sensor and the modulation signal to ultimately generate a modulated sensor signal $f_i \pm f_m$.

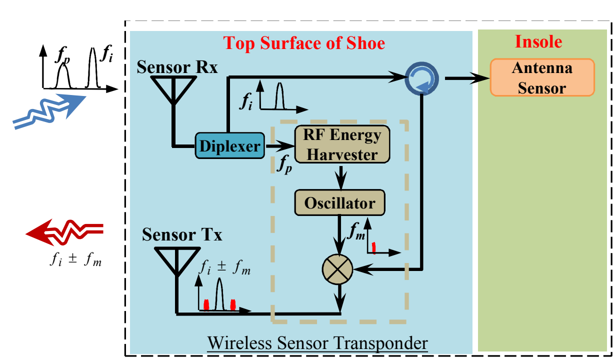


Figure. 1. Proposed wireless interrogation system.

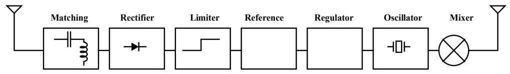


Figure. 2. Proposed sensor identification system.

The amplitude of the modulated signal is therefore directly proportional to the amplitude of the signal reflected by the antenna sensor.

When the interrogation frequency f_i matches the resonant frequency of the antenna sensor, the reflected signal has a small amplitude. On the other hand, the reflected signal increases in amplitude as the interrogation signal moves away from the resonant frequency of the antenna sensor. By transmitting the modulated sensor signal using the Tx antenna, a wireless receiver similar to those described in [8] can be implemented to demodulate the received sensing signal. Based on the frequency-amplitude relationship of the demodulated sensor signal, the resonant frequency of the antenna sensor can be determined. The advantage of the wireless interrogation is that the oscillator is the only component that consumes power. Since it consumes very low power, a RF energy harvesting system can be used to power up the oscillator [9,10]. Fig. 2 shows the proposed sensor identification system. The RF energy harvester system consists of a rectifier, limiter, reference and voltage regulator designed to power up the oscillator. The rectifier converts the received RF signal to DC and powers up the entire identification block. The voltage regulator generates a clean and regulated signal for the crystal oscillator. The pre-set frequency of the oscillator determines the frequency of the modulated signal. By implementing a different oscillator frequency for each sensor node, the signal from each sensor can be uniquely identified.

III. Circuit Design

To eliminate the need for a battery, a RF energy harvester is used. The RF signal is received by an antenna and converts to a DC signal through the rectifier. The DC power then is used as a power supply for the crystal oscillator and the mixer. To reduce power consumption, a passive mixer is presented.

A. *Energy harvester system*

1) *Rectifier and Limiter*

A 10-stage conventional diode connected MOS transistor rectifier is used in this design. The RF is received by the Rx antenna. A matching circuit is used to match a 50 Ω antenna to the input of the rectifier to transfer maximum power. The coupling capacitor C is used to transfer the electric charge in every cycle. The output voltage is calculated by:

$$V_{out}=N\,(V_{in}\ -V_{th}) \qquad (1)$$

where N and V_{th} are defined as the number of stages and threshold voltage of the NMOS transistors, respectively. From (1), the output voltage depends on the number of stages and the threshold voltage. Therefore, it is important to select an optimal number of stages. Adding more stages to the rectifier will increase the parasitics, which can reduce the overall Q of the circuit. Thus the optimal number of stages can be extracted from simulation and was chosen to be 10 in this design [11].

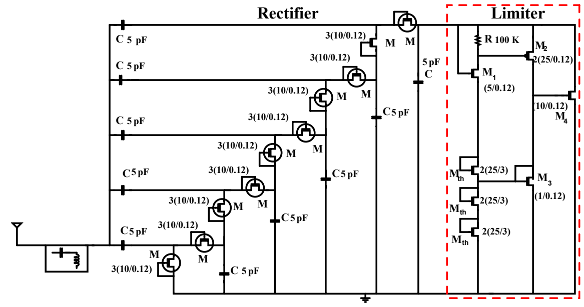


Figure. 3. Diode connected MOS rectifier and the limiter circuit.

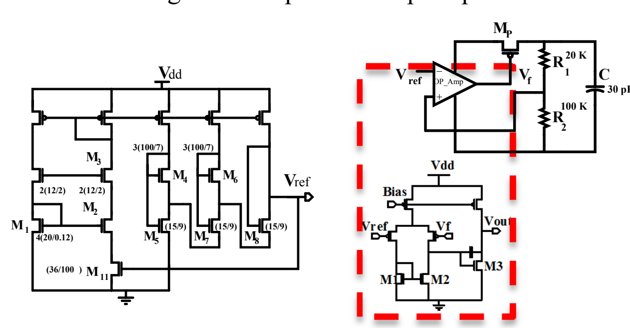
The rectifier is followed by a limiter to keep the output voltage below 1.2V, which is the maximum allowable power supply for this process. A target voltage is set by the three-threshold voltage M_{th}. When the rectifier voltage exceeds that of the target voltage, a bypass path (M_2) turns on and the excess rectifier current is pulled away by M_4 [12]. Fig. 3 shows the 10-stage rectifier and the limiter circuit.

2) *Voltage Reference and Voltage Regulator*

The next block of the energy harvester is a voltage reference, which generates a constant and stable voltage irrespective of supply voltage and temperature variations.

As illustrated in Fig. 4 (a) a fully CMOS voltage reference is implemented to provide 460 mV output voltage. This circuit is able to operate in the subthreshold region with minimum power consumption. The start up circuit and the operational amplifier that biases the gate of M3 are not shown in the picture for simplicity. M1-3 along with M11 generate a proportional to absolute temperature (PTAT) current. By passing that current through M4-8, a reference voltage is generated. All transistors operate in the subthreshold region other than M11. Instead of using the ordinary resistor, the MOS resistor M11 is implemented. Therefore, M11 operates in the deep triode region [13].

Fig. 4 (b) shows the conventional voltage regulator employed in the energy harvester system [14]. The linear voltage regulator consists of an error operational amplifier (op-amp), a pass transistor, and a resistive divider feedback network. The voltage regulator employs negative feedback to regulate the output for varied load conditions and changes in the supply voltage. The output voltage is sampled with the resistive divider network to V_f to compare it with the reference voltage at the input of the op-amp. The error



(a) (b)

Figure. 4. (a) Reference voltage [13], (b) voltage regulator [14].

amplifier generates a voltage drive for the pass transistor to control the current and regulate the output voltage. The resistor values and the reference voltage define the regulated output voltage [14]:

$$V_{Reg}=V_{ref}\,(1+R_1/R_2) \qquad (2)$$

B. Crystal Oscillator

A crystal oscillator is used to provide a precise frequency and low phase noise for designs that require high frequency stability. The crystal unit can be modeled as an electrical circuit. Fig. 5 shows the crystal oscillator schematic and the equivalent circuit model for the crystal (highlighted with dashed lines). L_1=127 mH and C_1 = 12.38 fF are the motional inductance and the capacitance respectively, while R_1=29 Ω is the series resistance and C_0 is the shunt capacitance. The crystal oscillator frequency is defined as:

$$f=\frac{1}{2\pi\sqrt{L_1\frac{C_0C_1}{C_0+C_1}}} \qquad (3)$$

The crystal oscillator is designed to operate at the frequency of 4 MHz with a phase noise of -151 dBc/Hz. To boost up the output swing, a level shifter and a buffer are designed after the oscillator. An off-chip crystal with high quality factor is used in this design.

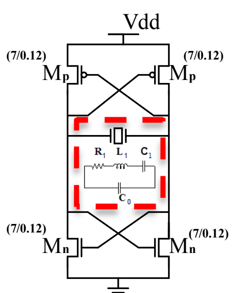


Figure. 5. Crystal oscillator and equivalent circuit model for the crystal.

C. Passive Mixer

The proposed passive mixer is shown in Fig. 6. The mixer operates like a switch. The local oscillator (LO) clock is applied to the gate of the switch while RF is connected to the source. When the LO is zero, M_1 is on and M_2 is off and the RF signal is matched to R which is 50 Ω. When the LO is one, M_1 is off and M_2 is on and the RF is mixed with the LO. An off chip matching network is designed to match the RF and IF ports. The RF and LO frequency are 5.8 GHz and 4 MHz, respectively.

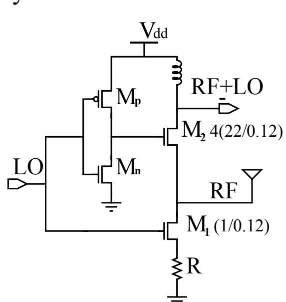
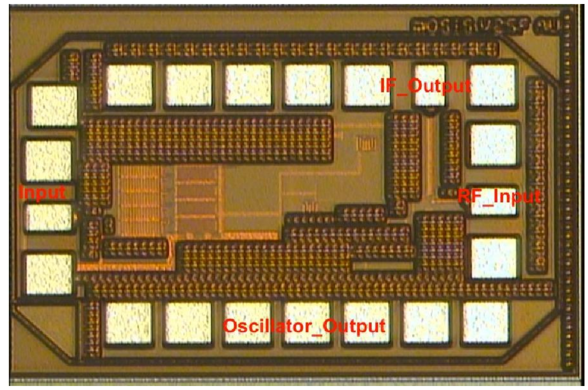
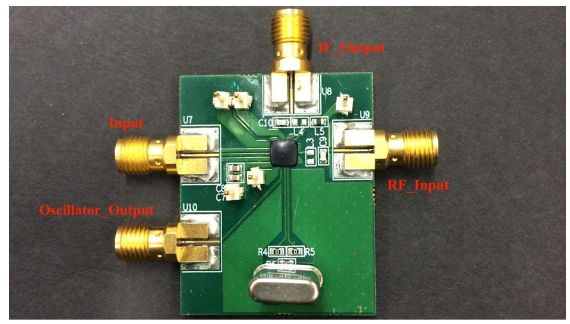


Figure. 6. Passive mixer.



(a)



(b)

Figure. 7. (a) Die photo (1.2mm x 0.8mm);
(b) The wire-bonded chip on a PCB.

IV. MEASUREMENT RESULTS

The wireless transponder was fabricated in IBM 130nm technology. The chip size is 1.2 mm × 0.8 mm. The chip was wire bonded onto the printed circuit board (PCB) for measurement. Fig. 7 (a) and Fig. 7(b) show the die photo and the wire bonded chip, respectively. The input signal with a frequency of 5.8 GHz and power of 7 dBm is applied to the input port. Since the receiver will be located on the subject's belt, there is no limitation on the input power. The distance between the interrogator and the sensor is assumed to be 1.5 m. According to the Frii's equation, the power transmitted by the interrogator should be 45 dBm in order to achieve an input power of 7 dBm for the energy harvester, assuming the gains of both the interrogator and sensor antennas are 6 dBi. The effective isotropic radiated power (EIRP) of the interrogator antenna is therefore 51 dBm, which is below the maximum EIRP of 53 dBm allowed by the Federal Communication Commission (FCC). Fig. 8 illustrates the measured rectifier and limiter output voltages versus the input power. When the input power is increased above 9 dBm the limiter bounds the output voltage to 1.2 V by driving current from the rectifier.

The 0.46 V voltage is generated by the reference voltage for the voltage regulator. Fig. 9 shows the measured output of the reference voltage versus the supply voltage variation. The total simulated power consumption of the system is 700μW.

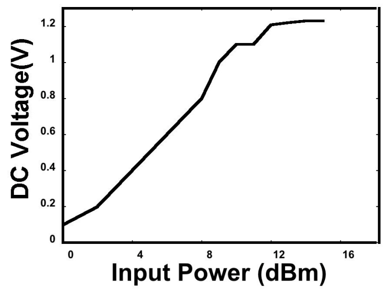


Figure. 8. Measured rectifier output voltage vs input power.

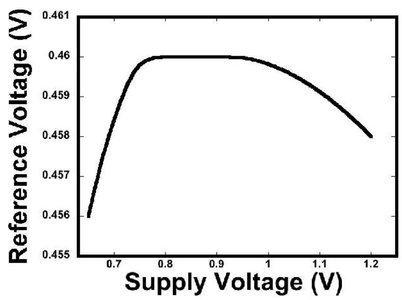


Figure. 9. Measured reference voltage vs. supply voltage.

The time domain measured result of the crystal oscillator is shown in Fig. 10. The frequency extracted is 3.88 MHz versus the 4MHz-simulated frequency.

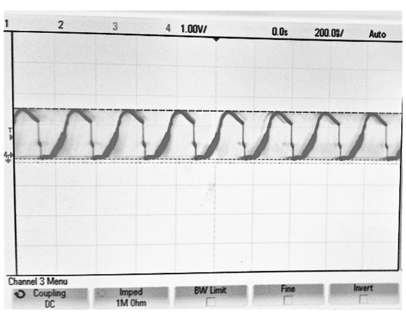


Figure. 10. Extracted frequency of the crystal oscillator with oscilloscope.

To measure the mixer, an external signal is applied to the RF port and the IF = (RF ± LO) power is measured by an Agilent spectrum analyzer. The RF frequency is 5.8 GHz with the power of -5 dBm. The intermediate frequency (IF) is measured at 5.804 GHz and the conversion loss is -20.76 dBm. Fig. 11 shows the measured IF power output.

V. CONCLUSION

A smart shoe transponder for antenna-based sensors operating at a frequency of 5.8 GHz is presented. An energy harvester system is implemented in the wireless transponder to eliminate the battery and to increase the operational time of the system. The advantage of this system is that the antenna sensors can be integrated with the wireless interrogation onto a single chip. We designed and measured the entire identification system including the energy harvesting blocks, crystal oscillator and passive mixer.

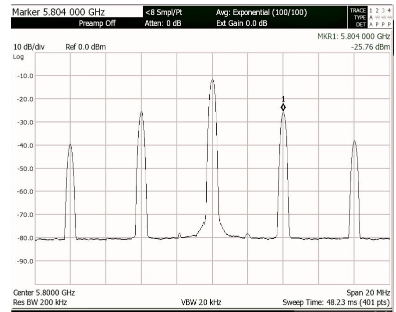


Figure. 11. Measured IF power at 5.804 GHz and harmonics.

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