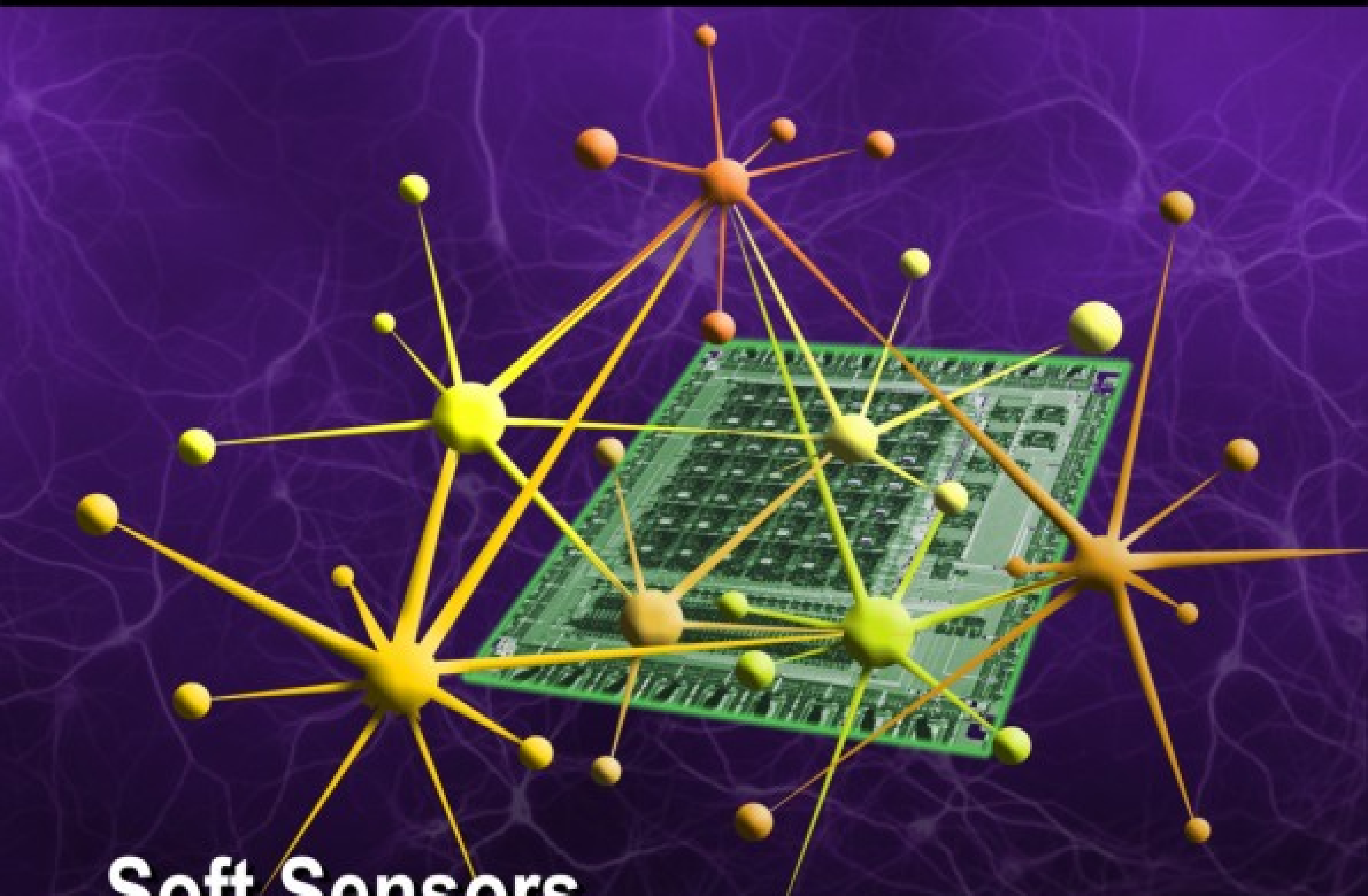
ISSN 1726-5749

SENSORS & TRANSDUCERS

10/07
vol. 84



Soft Sensors and Artificial Neural Networks

International Frequency Sensor Association Publishing

Sensors & Transducers

Volume 84
Issue 10
October 2007

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal

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Volume 84
Issue 10
October 2007

www.sensorsportal.com

ISSN 1726-5479

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International Frequency Sensor Association (IFSA).

Sensors & Transducers Journal, Vol.84, Issue 10, October 2007, pp. 1625-1632

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

A Low-Power Signal Processing Unit for *in vivo* Monitoring and Transmission of Sensor Signals

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Received: 29 September 2007 /Accepted: 23 October 2007 /Published: 30 October 2007

Abstract: A low-power signal processing and telemetry circuit for any generic biosensor applications has been presented. The complete system manifests a potentiostat, a signal processing block and a modulator block. The on-chip potentiostat biases the sensor electrodes for proper extraction of the sensor signals. The signal processing block integrates and buffers the sensor signal to make it a data signal and finally a simple modulator block converts this data signal to an on-off-keying (OOK) signal with a high frequency carrier. Package pin of the fabricated circuit is used as an antenna and measurement results demonstrate the successful signal transmission from the chip within a few cm ranges. The entire system has been realized using 0.35 μm CMOS technology that consumes only 400 μW of power and occupies an area of 0.66 mm^2. Test results show that this scheme is an effective candidate for low-power sensor applications. *Copyright © 2007 IFSA.*

Keywords: Implantable, OOK signal, Low-power device, Transmitter

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1. Introduction

The realization of implantable complex analytical systems including sensors is feasible now-a-days, because of the high degree of miniaturization of many classic measurement techniques [1]. Several research efforts have been reported for continuous *in vivo* measurement and monitoring of various physiological variables such as monitoring of the blood glucose level [2-4], lactate in the bloodstream or tissues [5], and pressure in blood vessels or intracranial compartments [6]. In most cases the sensor output is an analog current signal, which needs to be further processed and transmitted out of the biological environment (i.e. human body) so that the signal can be detected externally for analysis and initiation of necessary processing.

In order to monitor the senor signal remotely, the implantable sensor unit needs to include a transmitter. Transmission of sensor signals is becoming an essential part for the development of implanted unit. Signal telemetry provides the elimination of electrical artifacts due to the movements of cables in tethered measurements, and the reduction of the risk of skin irritation or infection caused by precutaneous leads in bioimplantable microsystems. A 16-channel wearable telemetry system for single-unit neural recording has been reported by Obeid *et al.* [7]. The entire system measures 5.1×8.1×12.4 cm^3, weighs 235 mg, and dissipates 4 watts of power from rechargeable lithium-ion batteries. Obviously the discrete board-level designs with commercially available electrical components have either prohibitively large dimensions and weight or high power consumption that makes them impractical for general-purpose low-power applications.

Monolithic integration of sensors and signal processing unit offers a power and area efficient design of the implanted system. Johannessen *et al.* have reported a microelectronic pill fabricated in a 0.6 µm CMOS process that consumes 12.1 mW of power, measures 5.5×1.6 $cm^{2,}$ and weighs 13.5 gm including two silver-oxide batteries [8]. Recently Mohseni *et al.* have developed miniature wireless frequency-modulated systems for biopotential recording and telemetry applications with substantially lower power dissipation per number of recording channels. The total chip area is 4.84 mm^2, and the power consumption is 2.2 mW with a 3 V power supply [9]. Most of these approaches are complex, power hungry and large in area, and only a few of them have on-chip biasing options of the corresponding sensors.

In the present work, we are proposing an area and power efficient integrated circuit solution for signal processing and transmission of a sensor signal with relatively simpler circuitry, and on-chip sensor biasing facility. The small area consumption of 0.66 mm^2 and especially very low power dissipation factor of 400 µW make it a suitable candidate for implantable biosensor applications. Package pin of fabricated IC has been successfully used as an antenna that eliminates the tedious approach of antenna design for short range communication. For this design, the test results yield the power consumption to be around 400 µW for a capacitive load of 100 pF and the signal transmit range is 1.5 cm which is good enough to transmit the data through human skin. In Section 2, we present a detailed description of the proposed design. In Section 3, we present the test setup and results of the fabricated chip. We summarize and draw conclusions in Section 4.

2. System Architecture

Fig. 1 shows the block diagram of the proposed design. The complete circuit consists of mainly three fundamental blocks: a potentiostat, a signal processing block and a modulator block. The potentiostat biases the sensor electrodes for proper operation of the sensor. The extracted sensor current is first processed to produce the envelope or data signal. In order to provide enough frequency separation between the data and the carrier signal, a programmable divider is incorporated before modulating the signal. Finally the modulator block modulates the data signal with a high carrier frequency and a driver unit drives the antenna with high gain for successful transmission of the signal. The fabricated IC in mounted in a dual in-line package (DIP) and a pin of this package is used as an antenna. Qualitative measurements demonstrate that the transmitted signal is strong enough for successful transmission within the range of a few centimeters. The descriptions of these blocks are as follows.

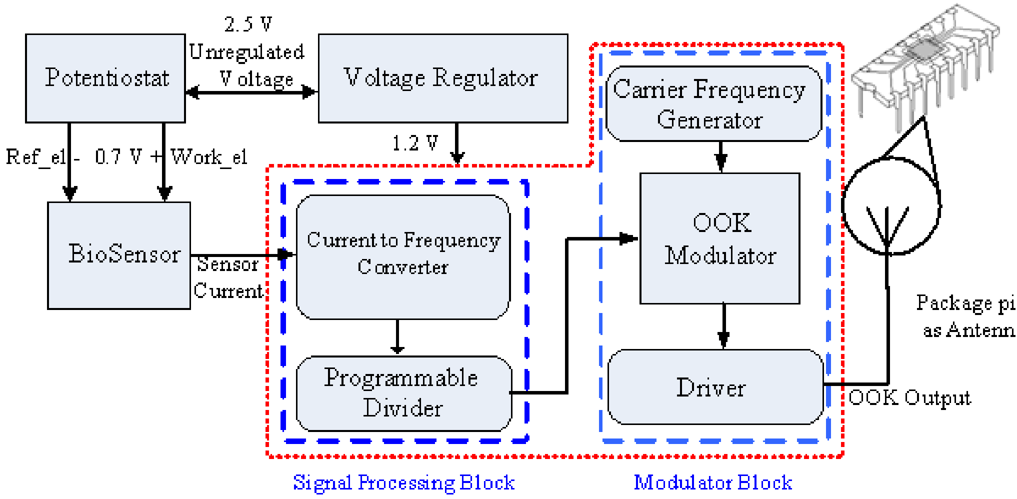


Fig. 1. Architecture of the complete system.

2.1. Potentiostat

Fig. 2 shows the block diagram of the potentiostat. It maintains a fixed voltage difference (0.7 V for example) between the working electrode (*work_el*) and the reference electrode (*ref_el*) for proper extraction of the sensor signal. U1 to U4 are operational amplifiers that are the building blocks of the potentiostat.

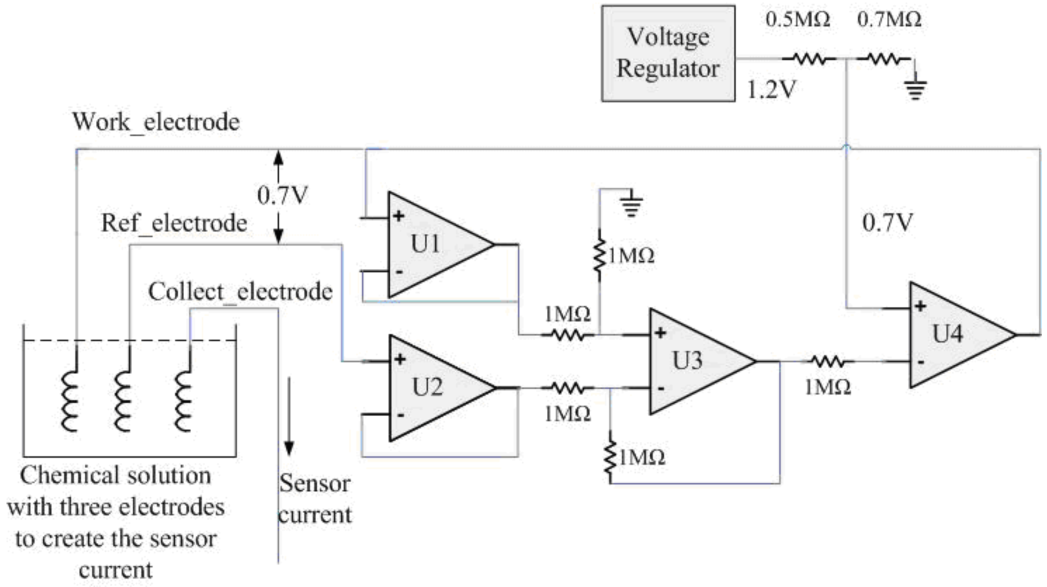


Fig. 2. Block Diagram for the potentiostat circuit.

The operating principle of the potentiostat is as follows. U1 and U2 work as buffers, U3 works as a unity gain differential amplifier and finally U4 works as an error amplifier. The non-inverting terminal of the error amplifier is maintained at a stable 0.7 V reference voltage. Therefore, any deviation from 0.7 V voltage difference between the *work_el* and *ref_el* is immediately compensated by feeding back the output of the error amplifier. By applying KCL at the inverting terminal of U3 (assuming ideal Op-Amp), we can get the following equation [10]:

$$V_{ref\_el} - \frac{V_{work\_el}}{2} = \frac{V_{work\_el}}{2} - 0.7 \quad , \qquad (1)$$
$$\therefore V_{work\_el} - V_{ref\_el} = 0.7$$

where, V_{ref_el} and V_{work_el} are the potential of reference and the working electrodes, respectively.

2.2. Signal Processing Block

Fig. 3 shows the block diagram of the signal processing and the modulator units. The signal processing block is designed to produce a data based on the sensor signal, which is further processed by the modulator block to generate the OOK signal. The signal processing block is fed a sensor current that can be generated by any implantable electrochemical sensor. The diode-connected NMOS (N1) in the input current mirror (N1, N2) stabilizes the voltage of the *Collect_el* terminal of the potentiostat to be about the threshold voltage (V_{th}) of the NMOS. The mirror current in N2 charges the integrating capacitor to the supply voltage resulting in a decreasing voltage at the input of the Schmitt trigger. Whenever the voltage falls below the threshold voltage of the Schmitt trigger, the feedback voltage from output turns the PMOS switch on and discharges the capacitor to start the new cycle. The mirror current controls the charging rate of the capacitor, which is in turn proportional to the sensor current. Thus the oscillation frequency is directly proportional to the sensor current level.

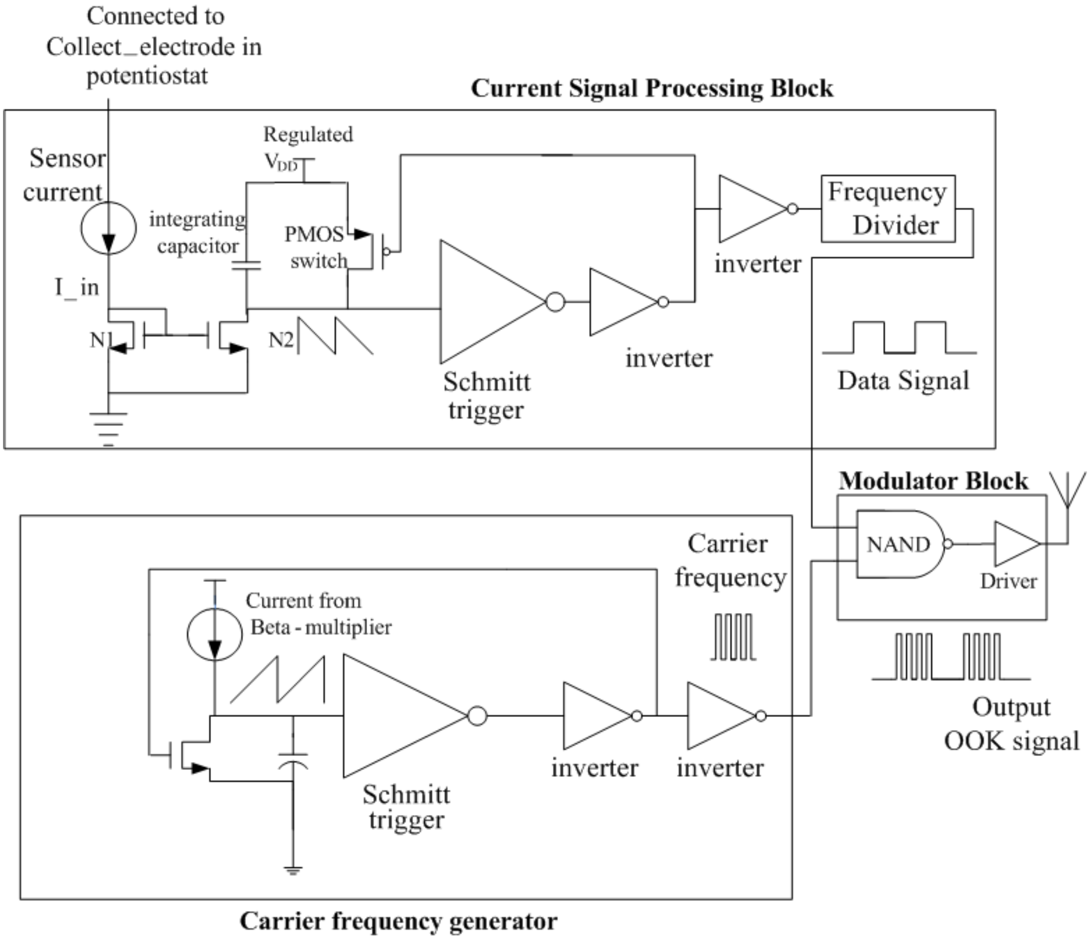


Fig. 3. Block diagram of the signal processing and the modulator units.

The entire circuit is designed to consume very small amount of power and to work with a very low supply voltage. A voltage regulator is designed to supply a stable V_{DD} (approximately 1.25 V) for the signal processing block. To ensure the carrier frequency is much greater than the sensor signal frequency, a programmable frequency divider is used to divide the data signal frequency by factors of 2, 8, 32, or 128 to produce a proper output frequency in the audible range.

2.3 Modulator Block

The modulator block modulates the data signal with a high frequency carrier to generate the OOK signal, which can be received and demodulated by a commercial radio. A simple ‘NAND’ gate is used as a modulator and a large W/L ratio inverter is used as a driver to drive the DIP package pin as an active antenna.

3. Test Results

The prototype IC was fabricated using 0.35 μm 2-poly 4-metal bulk CMOS process. Fig. 4 shows the micrograph of the fabricated chip.

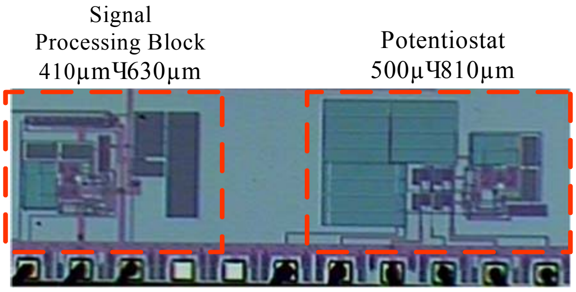


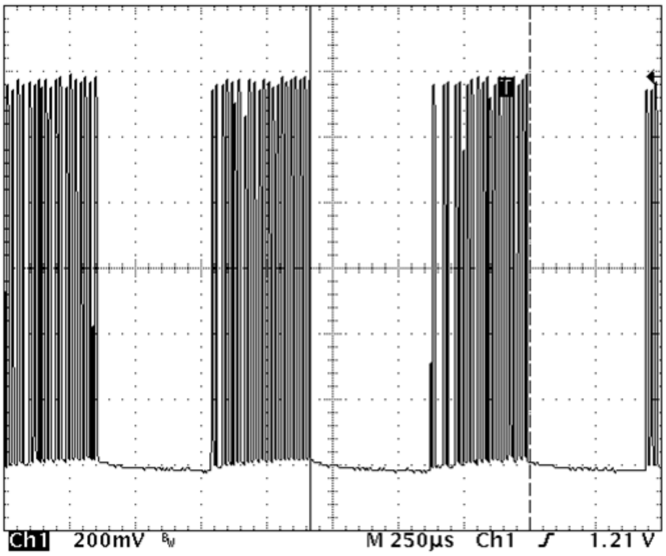
Fig. 4. Chip microphotograph.

From the test results as shown in Fig. 5, we can found the OOK signal output for a sensor current of 2.59 μA. Test results also reveal that with a 2.8 V unregulated supply voltage the power consumption is 400 μW on average. The carrier frequency is around 924.3 KHz, which is within the AM frequency range. The voltage regulator output is around 1.31 V. To generate a current similar to sensor current, two equal value resistors are used in between the electrodes; one is in between the *work_el* and *ref_el* and the other one is in between the *ref_el* and *collect_el*. This circuit arrangement is based on the assumption that whenever the electrodes are immersed in the chemical solution, there would be a certain resistance of chemical solution between any two electrodes. The current flowing through the resistors is therefore expressed as [10]:

$$I = \frac{V_{work\_el} - V_{ref\_el}}{R} = \frac{0.7}{R} \tag{2}$$

$$\text{Since } \frac{1}{\tau} \propto I = \frac{V_{work\_el} - V_{ref\_el}}{R} \quad , \quad \text{we should have } \frac{\tau_1}{\tau_2} = \frac{R_1}{R_2} \tag{3}$$

where, τ is the integration time of the sensor current. This implies that the envelope frequency of the OOK signal is proportional to the output current of the sensor. In this work, DIP package pin of the fabricated IC is used as an antenna. Fig. 6 shows the received signal from the antenna located at a distance of 1.5 cm from the receiving terminal. In Fig. 6, though the carrier signal is present at both high and low bit positions, their relative dc shift helps to recover the data using a simple envelop detector. As a proof of the data regeneration capability of this received signal, a wire was connected to the antenna of a commercial radio receiver and the wire was placed within the 2 cm range of the DIP package transmitter pin. Different tones were heard in the radio receiver for different sensor current levels which obviously demonstrate the different data frequency for different sensor currents. Finally, Fig. 7 illustrates the findings in terms of OOK signal envelope period vs. sensor equivalent resistance plot for three different chips with corresponding R-squared data. For each of the three fabricated chips, the standard R-squared value is very close to unity which reveals the linear performance of the system with the variation of sensor signal.



Resistor between *ref_el* and *work_el* is 270 Kohms

Fig. 5. Measurement Output of the OOK Signal for sensor current of 2.59µA.

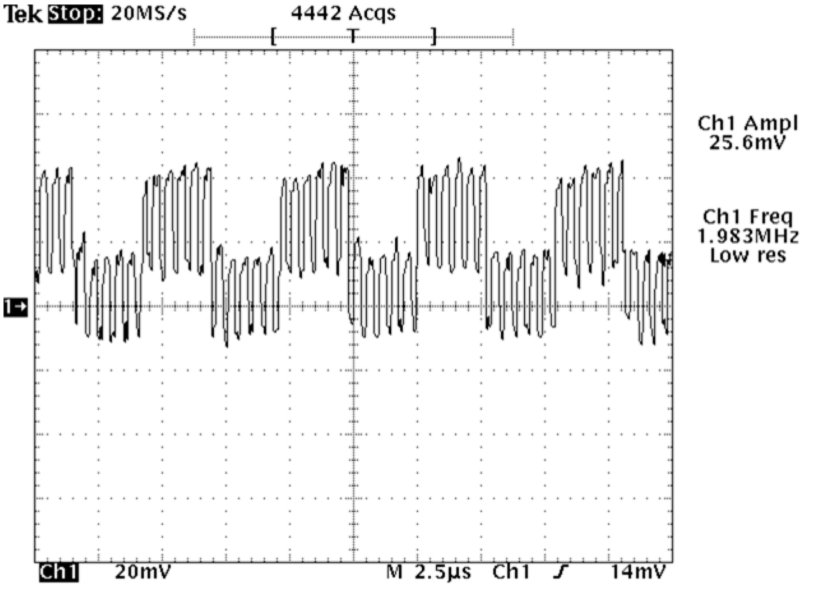


Fig. 6. Received Signal from the antenna (using the pin like an antenna) located at a distance of 1.5cm from the receiver.

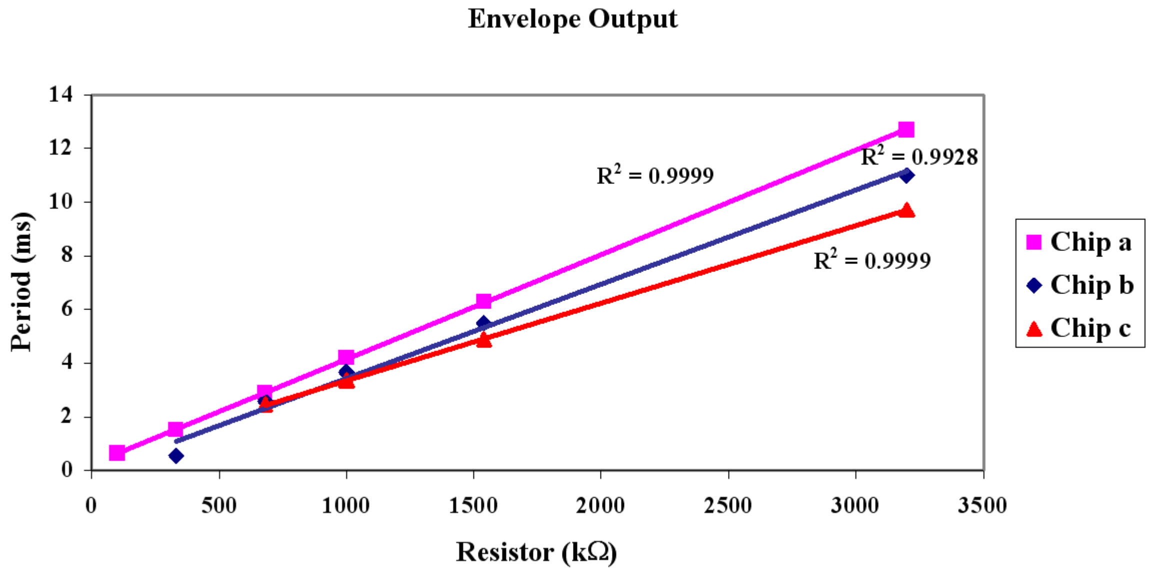


Fig. 7. Relationship between the envelope period and the sensor equivalent resistance.

4. Conclusions

A low power current signal processing circuit with sensor signal transmission capability has been demonstrated using standard CMOS process. The proposed scheme consumes very small amount of power and generates an OOK signal, which can be received and detected by a commercial radio receiver. Successful uses of package pin as an active antenna eliminates the need of tedious design approach for antenna design. This low power circuit topology offers the feasibility of designing a sensor chip powered by inductive link for long term stability of monitoring various physiological parameters from an implanted unit. Future work will include an integrated electrochemical sensor with a miniature on-chip antenna to increase the transmit range within an appreciable limit.

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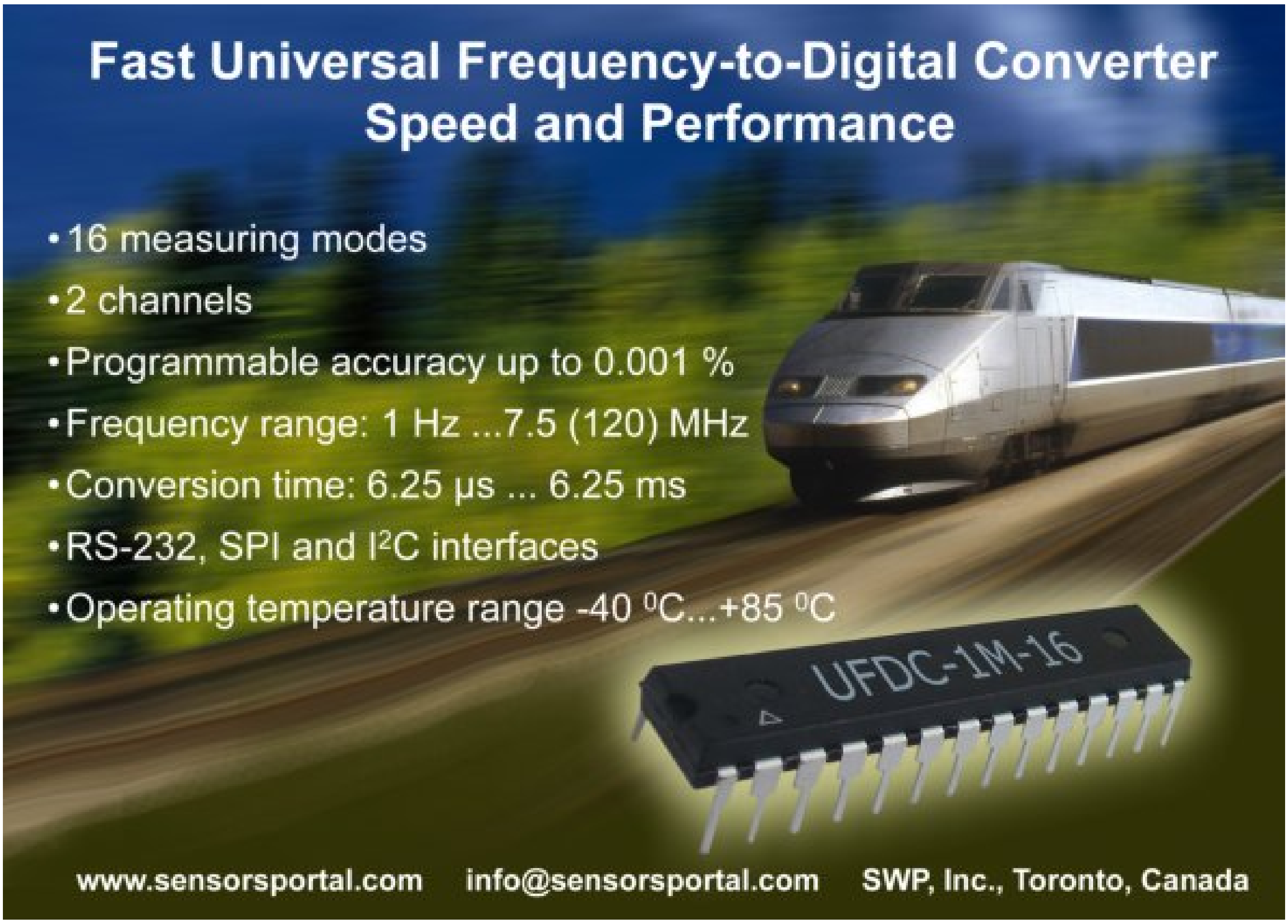

Sensors & Transducers Journal

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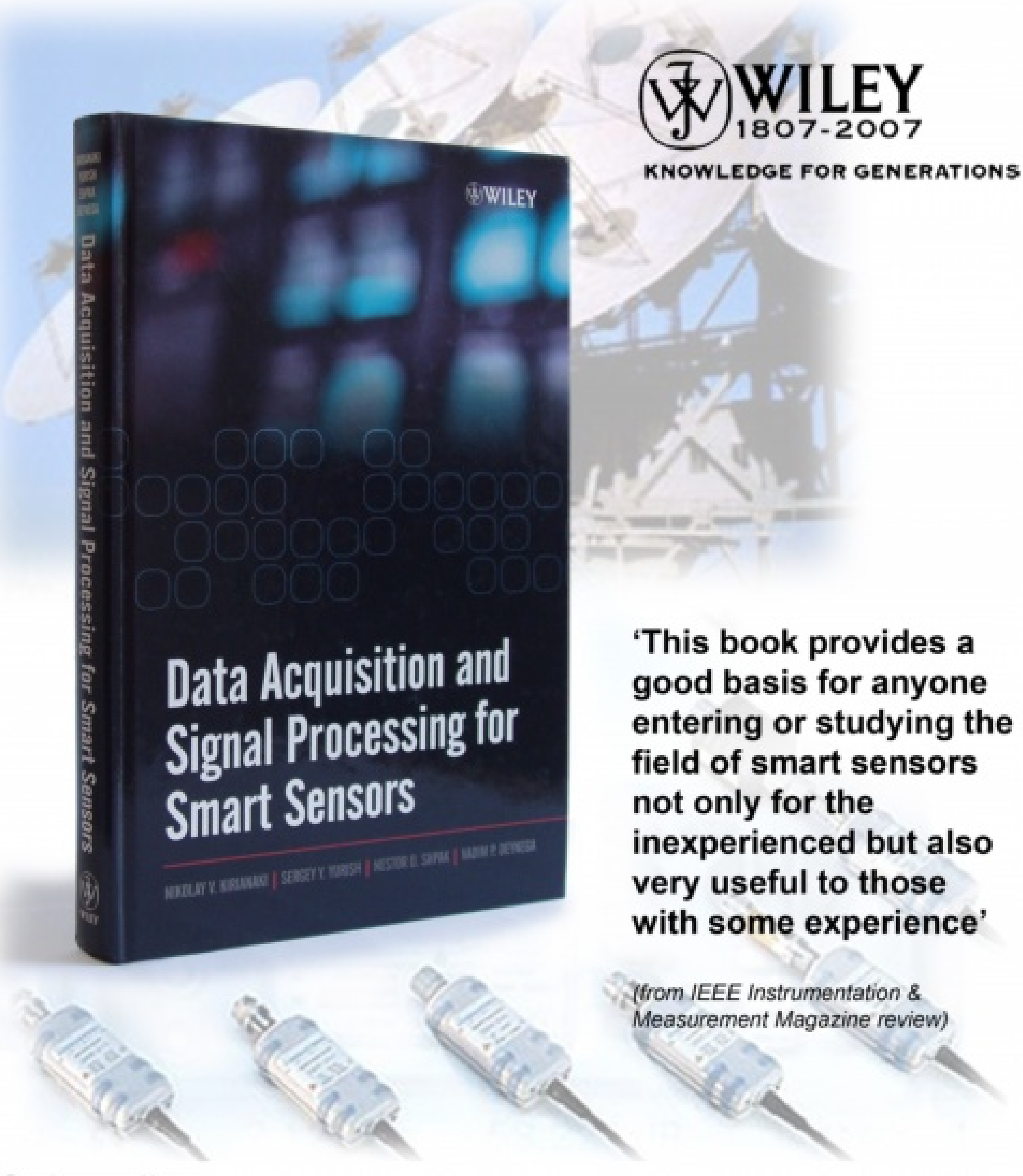
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