

Self-powered Motion Tracking Sensor Integrated with Low-power CMOS Circuitry

Nishat T. Tasneem, Dipon K. Biswas,
Ifana Mahbub
Dept. of Electrical Engineering
University of North Texas
Denton, Texas, USA
0000-0003-2489-7011

Pashupati R. Adhikari
Dept. of Mechanical
and Energy Engineering
University of North Texas
Denton, Texas, USA

Russell Reid
Dept. of Engineering
Dixie State University
St. George, Utah, USA

Abstract—This paper presents a motion-sensing device with the capability of harvesting energy from low-frequency motion activities that can be utilized for long-term human health monitoring. The energy harvester used in the proposed motion sensor is based on the mechanical modulation of liquid on an insulated electrode, which utilizes a technique referred to as reverse electrowetting-on-dielectric (REWOD). The generated AC signal from the REWOD is rectified to a DC voltage using a Schottky diode-based rectifier and boosted subsequently with the help of a linear charge-pump circuit and a low-dropout regulator (LDO). The constant DC voltage from the LDO (1.8 V) powers the motion-sensing read-out circuitry, which converts the generated charge into a proportional output voltage using a charge amplifier. After amplification of the motion data, a 5-bit SAR-ADC (successive-approximation register ADC) digitizes the signal to be transmitted to a remote receiver. Both the CMOS energy harvester circuit including the rectifier, the charge-pump circuit, the LDO, and the read-out circuit including the charge amplifier, and the ADC is designed in the standard 180 nm CMOS technology. The amplified amplitude goes up to 1.76 V at 10 Hz motion frequency, following linearity with respect to the frequency. The generated DC voltage from the REWOD after the rectifier and the charge-pump is found to be 2.4 V, having the voltage conversion ratio (VCR) as 32.65% at 10 Hz of motion frequency. The power conversion efficiency (PCE) of the rectifier is simulated as high as 68.57% at 10 Hz. The LDO provides the power supply voltage of 1.8 V to the read-out circuit. The energy harvester demonstrates a linear relationship between the frequency of motion and the generated output power, making it suitable as a self-powered wearable motion sensor.

Index Terms—Charge amplifier, charge pump, LDO, motion sensor, reverse electrowetting-on-dielectric, SAR-ADC, rectifier.

I. INTRODUCTION

Research on wearable medical devices has been widely proliferated with the development of energy harvesters combined with the low-power electronics on flexible sensors. Continuous monitoring of human physical activities such as walking, running, etc. need to be self-powered devices in order to avail the uninterrupted power sources and avoid constant maintenance. In this effort, many energy harvesting technologies have emerged for years such as piezoelectric, electromagnetic, triboelectric nanogenerator (TENG), vibration-based energy harvesting, and reverse electrowetting-on-dielectric (REWOD) [1]–[5]. Among these energy harvesting technologies, REWOD has been demonstrated to be advantageous among the other techniques due to its ability to generate a moderate

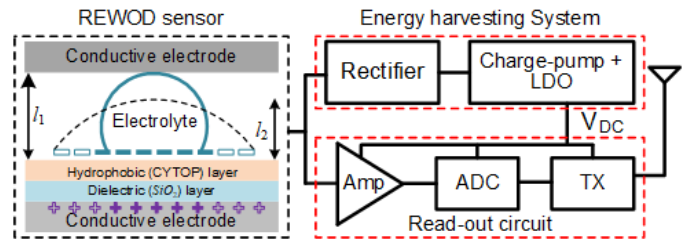


Fig. 1. Overview of the motion sensor with the working mechanism of REWOD energy harvesting system and the read-out circuit. Top plate is stationary while bottom plate oscillates vertically with applied mechanical modulation. Maximum mechanical displacement of electrodes during modulation, Δl is given as: $\Delta l = l_1 - l_2$.

amount of energy at a relatively low-frequency range of $\sim 1 - 10$ Hz [6], which is also a typical frequency range of various human physical activities [7]. Additionally, unlike other energy harvesters, REWOD harvesters does not require any solid structure resonance.

In this work, a self-powered motion sensor is developed by integrating a complementary metal-oxide-semiconductor (CMOS) chip with the REWOD-based energy harvester. Fig. 1 shows an overview of the system. The energy harvester includes a rectifier to convert the generated AC signal to DC voltage. Since the generated signal from the REWOD is a very low-frequency signal, large capacitors are required to store the charge, which is difficult to achieve on-chip. A charge-pump circuit is the most likely solution to amplify the DC voltage level. A cross-coupled charge-pump circuit is designed for energy harvesting purposes in [8]. However, the operating frequency of the proposed charge-pump system is in the MHz range. In this paper, a low-power switched-capacitor based charge-pump circuit for low-frequency operation (typically in few Hz range) is designed after the rectifier to boost the rectified DC voltage [9]. A low-dropout voltage regulator (LDO) followed by the charge-pump circuit is implemented to provide a constant DC voltage to the read-out circuit.

The generated charge from the REWOD device is fed to a charge amplifier that generates a proportionally amplified voltage at the output [10]. Prior works reported both commercial-off-the-shelf (COTS) and ASIC implementation of charge amplifiers for wearable sensors, but most of them are not suit-

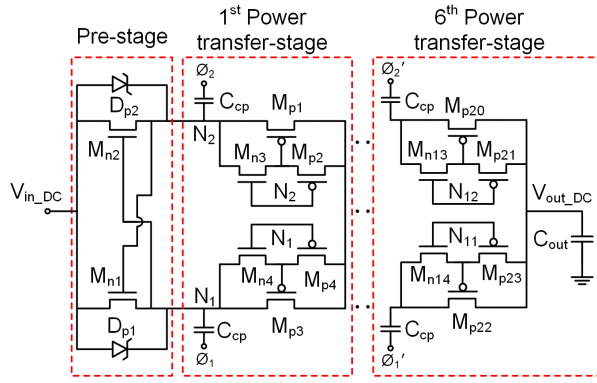


Fig. 2. Schematic of the six-stage charge-pump circuit.

able for low-frequency applications, such as motion sensing integrated electronics (IE) reported in [11], [12]. This paper presents the ASIC IE charge amplifier, providing a feedback path to obtain linearity in low-frequency movements [13]. The amplified voltage signal needs to be eventually digitized for wireless transmission to a remote end. The energy harvesting module of the REWOD system supplies the necessary power to the motion tracking low-power read-out circuit including the charge amplifier, and an analog-to-digital converter (ADC).

The contribution of the paper is as follows: design of a motion sensor, which is powered from the CMOS energy harvesting circuit. The low-power motion-detecting read-out circuitry is implemented on the same platform for making it completely self-powered. The overview of the motion sensor is presented in section II, section III discusses the results, and a concluding remark is presented in IV.

II. OVERVIEW OF THE SENSOR

A. REWOD Energy Harvester

Fig. 1 illustrates the working mechanism of the REWOD [6]. An external mechanical force is used to periodically deform the electrolyte droplet(s), thus inducing a periodic change in the contact area between the droplet and the dielectric-coated (SiO_2) electrode. This change in the contact surface area induces a change in the electric capacitance, C , and forces electrical current to flow back and forth across the load resistor, thus converting mechanical modulation into electrical energy. Electrically, REWOD could be modeled as a current source, a resistor, and a capacitor all in parallel. REWOD works as a current source across the parallel resistor due to the generated charge at the surface of the electrodes.

B. Energy Harvesting Circuit

The proposed energy harvester circuit consists of a rectifier, a charge-pump, and a low-dropout voltage regulator. The detailed description of the blocks are as follows.

1) *Charge-Pump Circuit*: The proposed DC boosting circuit uses a low-voltage, cross-coupled linear charge-pump architecture. The architecture can be divided into pre-stage and power transfer-stages as shown in Fig. 2. Six power transfer stages are cascaded in the proposed design to meet the voltage

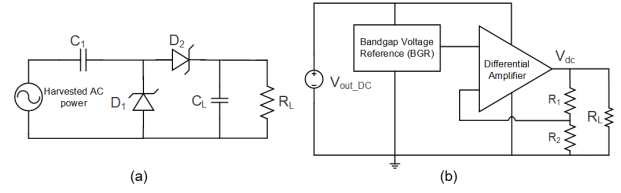


Fig. 3. (a) Schematic of a single-stage rectifier, (b) block diagram of the low-dropout regulator.

requirements of the target application. The complementary cross-coupled architecture is considered in this work. The two charge-pump circuits work at complementary clock pulses to provide the output. The cross-coupled stages also reduce the ripple of the output voltage which enables the desired performance from the low input frequency. The circuit includes a pre-stage voltage-doubler circuit implemented using nMOS transistors. After the pre-stage, six charge transfer stages are included, where the switching transistors are implemented using pMOS to avoid an increase in device threshold voltage due to the body effect. Two Schottky diodes (D_{p1-p2}) are used in parallel with the nMOS transistors (M_{n1-n2}) in the pre-stage to charge the capacitor C_p during startup. After charging the capacitor, the diodes are bypassed afterwards by having the sufficient gate-to-source voltage for the nMOS transistors to turn on. Two complementary signals, ϕ_1 and ϕ_2 control the adjacent charge-pump stages to reduce the possibility of reverse current flowing from a later stage to the previous stages in the circuit. During the clock transition period, the voltage at node N_1 goes from V_{in_DC} to $2V_{in_DC}$ and the voltage at node N_2 goes from $2V_{in_DC}$ to V_{in_DC} at the same time. During the transition, the NMOS switch connected to the node N_1 is completely turned off, thus eliminating the reverse current path.

2) *Rectifier*: The proposed rectifier architecture is a Schottky diode-based single-stage Dickson multiplier circuit as shown in Fig. 3(a) [14] which is used ahead of the charge-pump circuit. The time constants of the multiplier are designed to be substantially larger than the period of the generated signal from REWOD in order to minimize the ripple at the output of the rectifier. The input and output capacitance of the rectifier are chosen in such a way to satisfy the condition presented in Eqn. (1), where I_{rect} and V_{rect} are the output current and the output DC voltage, respectively. f is the frequency of the motion activity (oscillation frequency between the electrodes).

$$\frac{I_{rect}}{2\pi CV_{rect}} \ll f \quad (1)$$

The calculated capacitance is found to be $10 \mu\text{F}$ for the lowest motion frequency of 1 Hz. However, it is difficult to achieve such a high capacitance on-chip. For that reason, the off-chip commercially available capacitors are used for the rectifier circuit.

3) *Low-dropout Voltage Regulator Circuit*: The energy harvesting system also includes an LDO to maintain the output DC voltage from the charge-pump to a constant voltage level. The block diagram of the LDO is shown in 3(b). A

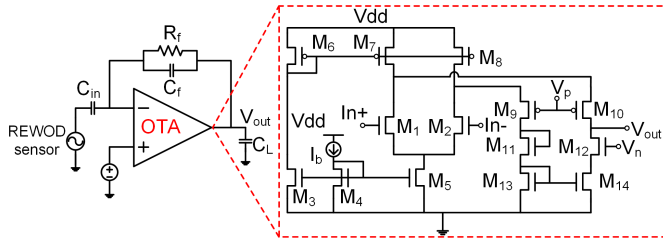


Fig. 4. Schematic of the amplifier with the OTA.

conventional bandgap voltage reference (BGR) and a two-stage differential amplifier form the LDO. A resistive divider consisting of R_1 and R_2 is used at the output, which helps reconfigure the output voltage level depending on the voltage requirements. R_{load} is used as the load that is emulated by the read-out circuit (Fig. 1).

C. Read-out circuit

Since the generated charge from the REWOD typically lies in a low-range value, implementing the charge amplifier allows an improved signal-to-noise ratio (SNR) by transducing the charge into an output voltage. The schematic of the amplifier with the operational transconductance amplifier (OTA) is shown in Fig. 4. A folded cascode architecture is implemented as the OTA [15]. The mid-band gain of the amplifier can be calculated as $A_M = C_{in}/C_f$, where C_{in} and C_f are the input and the feedback capacitances, respectively. C_{in} and C_f are chosen to be 1.8 pF and 0.9 pF, respectively to set the gain as 2 V/V. As the motion frequency increases, the amplified voltage increases and can be clipped beyond 1.8 V, which is the power supply for this design. The gain is chosen in such a way to amplify the signal at the highest frequency input to the amplifier. The output voltage, V_{out} is produced proportionately by converting the generated charge through C_{in} . C_{in} also eliminates the DC components from the input AC signal. The bandwidth of the charge amplifier is designed to detect human physical activities within the motion frequency.

A low-power 5-bit traditional SAR-ADC is designed to digitize the continuous motion data for wireless communication. The ADC can digitize as low as 50 mV amplified voltage from the REWOD. As the motion frequency occupies a low-frequency band (<10 Hz), a low-sampling rate of 1 ksamples/s is chosen for the ADC, presenting the trade-off between the power consumption and speed. A single-ended SAR architecture is designed in this work. The ADC consists of a sample and hold circuit, a binary charge scaling digital-to-analog converter (DAC), a dynamic comparator, and a SAR-logic circuit. The sampling clock frequency of the ADC is generated using an external crystal oscillator. The unit capacitor of the DAC is implemented using the process metal-insulator-metal (MIM) capacitor and is chosen to be 56 fF.

III. RESULTS

Electrodes were fabricated using a highly doped silicon wafer with a titanium conductive layer and SiO_2 dielectric layer, both using an E-beam evaporator. The thickness of the conductive layer was ~ 200 nm and that of SiO_2 was ~ 150

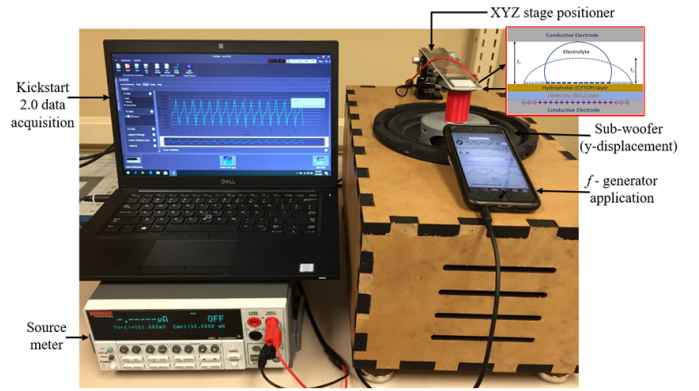


Fig. 5. Test setup of generating AC energy from REWOD harvester

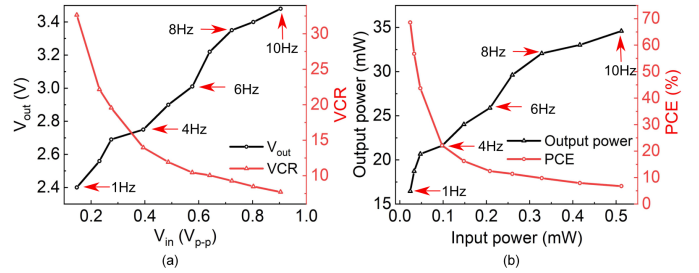


Fig. 6. Post-layout simulation result of (a) Rectifier and Charge-pump output voltage, V_{out} and VCR with respect to the harvested AC voltages at different frequencies, (b) Rectifier and Charge-pump output power and PCE with respect to the harvested AC voltages at different frequencies.

nm. For surface hydrophobicity, the CYTOP solution was deposited by spin coating to achieve ~ 50 nm thickness. 20 mL of glycerol-based electrolyte was prepared using 18.2 mL of 1 M NaCl solution and mixing it with 1.8 mL of glycerol. The presence of glycerol slows electrolyte evaporation. Modulation of the electrolyte is performed using a homemade subwoofer and a cellphone app (Function Generator PRO) to control the subwoofer frequency and amplitude, as shown in Fig. 5. Keithley Kickstart software (2.0) from Tektronix along with the sourcemeter (2400 Source Measure Unit (SMU)) is used to acquire the generated AC power. 50 μ L of electrolyte is placed on the lower electrode, and then the upper electrode is positioned so that the initial gap between electrodes is 4 mm. The modulation frequency range is chosen to be 1 - 10 Hz with a step size of 1 Hz. The generated AC voltage for the given frequency range was 147 mV to 943 mV with 1.0 M NaCl aqueous solution as an electrolyte. The range of the generated voltage from the REWOD is significant given the fact that it completely arose within the electrode-electrolyte interface without any external voltage source. With an objective to develop an energy harvester for self-powered wearable sensors, no external bias voltage/battery was applied.

The generated AC Voltage is rectified and boosted using the proposed rectifier and the charge-pump circuit, followed by the LDO. Fig. 6(a) shows the rectified output DC voltage and voltage conversion ratio (VCR) with respect to the generated AC peak-to-peak voltage. The input voltage, V_{in} represents the voltage harvested by the REWOD and fed to the input of the rectifier. The output voltage, V_{out} in Fig. 6 (a) represents

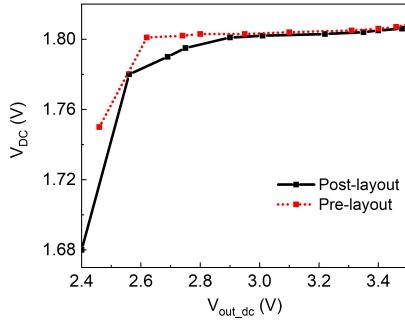


Fig. 7. Pre- and post-layout simulations of the LDO with respect to charge-pump output voltage.

the output of the charge-pump circuit. The circuits can provide as much as 2.4 V DC voltage for the lowest input AC voltage of 147 mV_{pp} at 1 Hz of modulation frequency. The calculated maximum VCR of 32.65% is achieved at the lowest input voltage for 1 MΩ load resistance, where the VCR is defined as the ratio of the output voltage and input voltage. The maximum achieved DC voltage is approximately 3.4 V for 943 mV_{pp} input AC voltage at 10 Hz frequency. The PCE of the rectifier and the charge pump circuit is also calculated as $PCE\% = P_{out}/P_{in} \times 100\%$. The generated output power and the PCE of the system are presented in Fig. 6(b). The maximum PCE is simulated to be $\sim 68.57\%$ at 10 Hz frequency with the load resistance and load capacitance as 1 MΩ and 10 μF, respectively. The charging and discharging time for the load capacitor is ~ 10 s for the given load condition. The LDO regulates the output voltage of the charge-pump circuit to maintain the supply voltage at 1.8 V. Fig. 7 presents both the pre-layout and post-layout simulations of the LDO. The x -axis represents the output voltage, V_{dc} which is coming from the charge-pump circuit and the voltage V_{dc} in the y -axis represents the output voltage of the LDO, that is used as the supply voltage for the read-out circuitry. The LDO provides almost constant voltage over the variation in the boosted DC voltage at the charge-pump circuit. The LDO is the only power consumption circuit in the energy harvesting circuit which consumes 1 mW power for 1.8 V supply voltage.

For detecting motion activities, the charge amplifier produces the output voltage that is proportional to the charge generated from the REWOD. Fig. 8(a) shows the closed-loop mid-band gain of the amplifier. The charge-amplifier achieves 7.6 dB of voltage gain (~ 2.4 V/V). The amplifier occupies the low-bandwidth of 0.2 - 17 Hz, which is applicable for the linear function of the sensor. The amplified output voltage over the modulation frequencies at 2.5 mm displacement between the electrode is presented in Fig. 8(b). It exhibits the linear operation of the converted voltage from the REWOD over the frequency range of 1 - 10 Hz. The amplified output voltage ranges from 294 mV - 1.7 V over the modulation frequency range of 1 - 10 Hz. The linear sensitivity of the charge amplifier can be quantified as the slope of the output voltage amplitude per unit of frequency change and is evaluated as 0.178 V/Hz. Fig. 9 shows a representative motion signal from the REWOD and its amplified voltage. The motion signal is

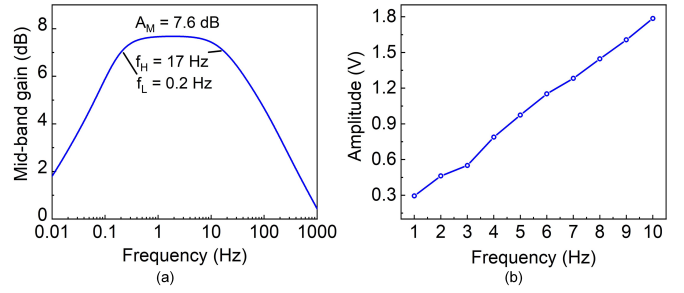


Fig. 8. (a) Closed-loop gain of the amplifier, (b) amplified output voltage from the REWOD.

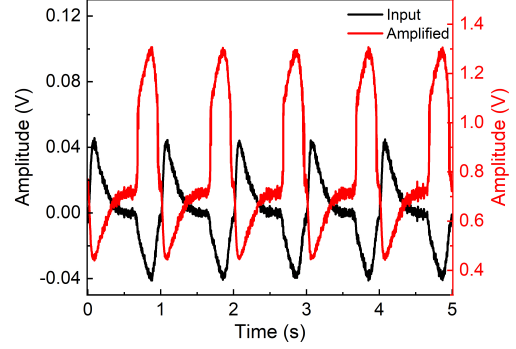


Fig. 9. Amplified output voltage from the REWOD.

imported to the simulation platform (Cadence) and is amplified in the designed amplifier. The amplified voltage is shifted to 0.9 V, which is the mid-rail voltage of the amplifier. The total power dissipation of the amplifier is as low as 1.95 μW, with the input impedance of 1.6 MΩ. The input impedance of the amplifier is matched with the equivalent impedance of the REWOD sensor to avoid the DC offset at the electrode-amplifier interface. The 5-bit SAR-ADC is also implemented on the same chip, with the sampling frequency of 1 ksamples/s. The power density from the REWOD energy harvester is found to be 58 nW/cm², which is sufficient to power the on-chip CMOS circuitry with a higher surface modulation area.

IV. CONCLUSION

This paper presents a motion-tracking sensor for the continuous monitoring of human physical activities. The mechanical modulation of REWOD without any external bias provides the supply voltage for the motion-sensing read-out circuit with the help of a CMOS energy harvester including a rectifier and a charge-pump circuit. The rectifier exhibits a power conversion efficiency of 68.57% at 10 Hz of modulation frequency, producing 3.4 V at the charge pump circuit. The read-out circuit consumes a low power of 1.95 μW, which is powered by the energy harvesting system. Eventually, the motion-sensing electrodes along with the on-chip circuitry with the transmitter will be implemented on a flexible substrate for wearable applications.

ACKNOWLEDGMENT

This material is based upon work supported by the National Science Foundation under Grant No. ECCS 1933502.

REFERENCES

- [1] Y. Peng, K. D. Choo, S. Oh, I. Lee, T. Jang, Y. Kim, J. Lim, D. Blaauw, and D. Sylvester, "An efficient piezoelectric energy harvesting interface circuit using a sense-and-set rectifier," *IEEE Journal of Solid-State Circuits*, vol. 54, no. 12, pp. 3348–3361, 2019.
- [2] L. Zhang, H. Dai, Y. Yang, and L. Wang, "Design of high-efficiency electromagnetic energy harvester based on a rolling magnet," *Energy Conversion and Management*, vol. 185, pp. 202–210, 2019.
- [3] G. Zhu, B. Peng, J. Chen, Q. Jing, and Z. L. Wang, "Triboelectric nanogenerators as a new energy technology: from fundamentals, devices, to applications," *Nano Energy*, vol. 14, pp. 126–138, 2015.
- [4] J. Siang, M. Lim, and M. Salman Leong, "Review of vibration-based energy harvesting technology: Mechanism and architectural approach," *International Journal of Energy Research*, vol. 42, no. 5, pp. 1866–1893, 2018.
- [5] T. Krupenkin and J. A. Taylor, "Reverse electrowetting as a new approach to high-power energy harvesting," *Nature Communications*, vol. 2, no. 1, pp. 1–8, 2011.
- [6] N. T. Tasneem, D. K. Biswas, P. R. Adhikari, R. Reid, and I. Mahbub, "Design of a reverse-electrowetting transducer based wireless self-powered motion sensor," in *2020 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2020, pp. 1–5.
- [7] T. Ji and A. Pachi, "Frequency and velocity of people walking," *Structural Engineer*, vol. 84, no. 3, pp. 36–40, 2005.
- [8] K. You, H. Kim, M. Kim, and Y. Yang, "900 MHz CMOS RF-to-DC converter using a cross-coupled charge pump for energy harvesting," in *2011 IEEE International Symposium on Radio-Frequency Integration Technology*, 2011, pp. 149–152.
- [9] C. Ulaganathan, B. J. Blalock, J. Holleman, and C. L. Britton, "An ultra-low voltage self-startup charge pump for energy harvesting applications," in *2012 IEEE 55th International Midwest Symposium on Circuits and Systems (MWSCAS)*. IEEE, 2012, pp. 206–209.
- [10] I. Mahbub, S. A. Pullano, H. Wang, S. K. Islam, A. S. Fiorillo, G. To, and M. Mahfouz, "A low-power wireless piezoelectric sensor-based respiration monitoring system realized in CMOS process," *IEEE Sensors Journal*, vol. 17, no. 6, pp. 1858–1864, 2017.
- [11] F. Wohlstreicher, "Charge amplifier for sensors outputting electrical charge," Dec. 6 1994, uS Patent 5,371,472.
- [12] S. Mizuno, K. Fujita, H. Yamamoto, N. Mukozaka, and H. Toyoda, "A 256×256 compact CMOS image sensor with on-chip motion detection function," *IEEE Journal of Solid-State Circuits*, vol. 38, no. 6, pp. 1072–1075, 2003.
- [13] A. J. Fleming and S. R. Moheimani, "A grounded-load charge amplifier for reducing hysteresis in piezoelectric tube scanners," *Review of Scientific Instruments*, vol. 76, no. 7, p. 073707, 2005.
- [14] G. De Vita and G. Iannaccone, "Design criteria for the RF section of UHF and microwave passive RFID transponders," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 9, pp. 2978–2990, 2005.
- [15] A. Simoni, G. Torelli, F. Maloberti, A. Sartori, S. E. Plevridis, and A. N. Birbas, "A single-chip optical sensor with analog memory for motion detection," *IEEE Journal of Solid-State Circuits*, vol. 30, no. 7, pp. 800–806, 1995.