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Ultra-low–power Pulse Oximeter with a 32.768 kHz Real Clock

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** Short Paper*

Abstract**:** A conventional pulse oximeter has high power consumption; thus, its mobility is severely limited. In this paper, we discuss the drawbacks of the existing pulse oximeters and propose a new ultra-low–power pulse oximeter that supports wireless data transmission for remotely monitoring vital signs, such as peripheral capillary oxygen saturation (SpO2) and beats per minute (BPM). We could notably reduce power consumption by using a low-frequency single clock in all well-customized modules. Also, our device is publicly certified, and thus, possibly engaged in clinical trials for commercial use.

Keywords**:** *SpO2*, *BPM*, Pulse oximeter, SoC, Wearable

1. Introduction

Recently, as the importance of personal health care increases, the demand for bio-medical devices that measure a person's vital signs is increasing dramatically. In particular, since peripheral capillary oxygen saturation (SpO2) and beats per minute (BPM) are among the most important vital signs, real-time monitoring of these data is very important when detecting someone's physical condition.

However, existing devices for measuring vital signs in real time consume too much power due to their low degree of integration and the requirement for high measurement accuracy [1, 3]. Furthermore, they do not support wireless transmission of the measured results to a remote monitoring system, so it is impossible to observe the vital signs remotely.

To overcome the limitations of the existing devices, these days, there are several studies into developing a low-power and portable pulse oximeter. One representative method is to use a general micro control unit (MCU), e.g. the MSP430 of Texas Instruments, for implementing a pulse oximeter [2]. However, the method is still limited by not providing additional functions like wireless data transmission in the hardware. Other methods implement various functions of a pulse oximeter in a full-custom design, but they are not optimized well, and thus, consume high levels of power [3]. Furthermore, no such oximeters have been formally certified by a public certification institution yet.

In this paper, we present a novel low-power and certified pulse oximeter that measures both SpO2 and BPM using a non-invasive method. Also, the pulse oximeter can transmit the measurement results wirelessly using radio frequency identification (RFID) technology to a remote monitoring system, e.g. a smartphone with a monitoring application. Since all the modules of our pulse oximeter are designed to operate at the same clock frequency of 32.768 kHz, we can optimally integrate the modules to alleviate dynamic power consumption in a way different from existing devices. In addition, our proposed device is publicly certified by the Korea Testing Laboratory [4], a certification institution under the Ministry of Food and Drug Safety in Korea [5], and hence, we confirmed the reliability of the device.

This paper is organized as follows. Section 2 describes

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the principle of a non-invasive method for measuring SpO2. Section 3 presents the architecture of our proposed device, and describes how it is optimized for reducing dynamic power consumption. Section 4 presents the implementation details of our proposed device and evaluates its performance. Finally, the conclusion is presented in Section 5.

2. Measurement of SpO2

There are two representative methods for measuring SpO2: invasive and non-invasive. Our proposed pulse oximeter is designed to use a non-invasive method for measurements. Its mathematical equations are as follows:

$$SpO_2 = \frac{HbO_2}{HbO_2 + Hb} \times 100 \tag{1}$$

$$R = \frac{i_{ac,R} / I_{DC,R}}{i_{ac,IR} / I_{DC,IR}} \tag{2}$$

$$SpO_2 = aR^3 + bR^2 + cR + d \tag{3}$$

where SpO_2 indicates the concentration ratio of blood oxygen saturation, HbO_2 and Hb mean the concentration ratios of hemoglobin combined and not combined with oxygen in the blood, respectively. Also, $i_{ac,R} / I_{DC,R}$ is the ratio of AC and DC components of red light(Red) and $i_{ac,IR} / I_{DC,IR}$ is that of infrared light(IR).

Eq. (1) presents a general formula for obtaining SpO2 by using hemoglobin concentration [6]. However, we do not know the value of Hb, because we employ a non-invasive method. Thus, *SpO2* is to be calculated by using the ratio of normalized absorbances (R) and coefficients *a, b, c,* and *d* in Eq. (3).

First, R represents a parameter that is used to calibrate SpO2 [6]. To obtain R using Eq. (2), we employed two different types of light, i.e. IR and Red, with their respective wavelengths slightly longer and shorter than 800 nm. Because hemoglobin (both bound and not bound with oxygen in the blood) has different absorption rates at near-infrared wavelength ranges, the light-absorption characteristics of hemoglobin are reversed near the 800nm wavelength.

Second, coefficients *a, b, c,* and *d* are the best-fit values obtained via the third-order polynomial curve in Fig. 1, which correlates with the measured R and SpO2 from a pre-calibrated pulse oximeter. Actually, the relation between R and SpO2 is derived from a great amount of clinical test data and static analyses. Hence, the coefficients are empirical values and are important because they determine the output of our proposed device. Although the conventional method uses a second-order polynomial [1], our proposed device employs a third-order polynomial for a more detailed calibration to be certificated by the public institution mentioned above.

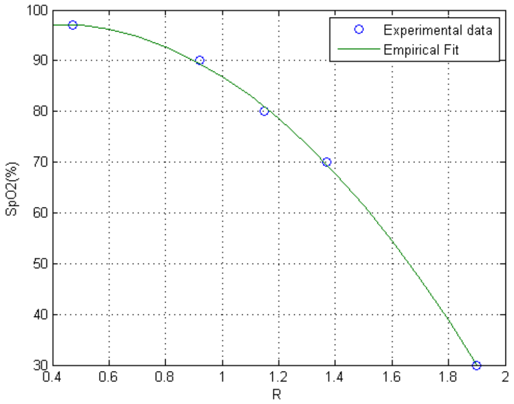


Fig. 1. Third-order polynomial calibration curve.

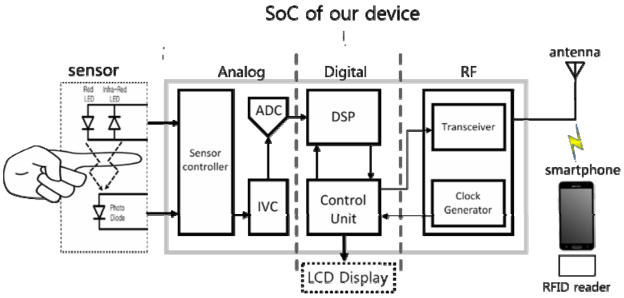


Fig. 2. An organization of our pulse oximeter.

3. Proposed Architecture for Low Power

In this section, we describe the overall architecture of our pulse oximeter and the design optimization for the reduction of dynamic power consumption.

3.1 Overall Architecture

Fig. 2 shows the detailed design of our pulse oximeter. The pulse oximeter system on a chip (SoC) mainly consists of the following three parts: analog, digital, and radio frequency (RF).

The analog part is comprised of a sensor controller with an analog-digital converter (ADC) and a current-voltage converter (IVC). The sensor controller is basically designed to support non-invasive pulse oximetry that employs light sources of a sensor. The sensor is comprised of a photodiode and two LEDs, i.e. Red and IR. The photodiode detects the absorbed or passed light while Red and IR light passes through the finger, as shown in Fig. 2. Then, the sensor controller measures the amount of light that is either reflected or absorbed, and transmits the output signal in current form, i.e. $i_{ac,R}$, $I_{DC,R}$, $i_{ac,IR}$, and, $I_{DC,IR}$, to a digital signal processor (DSP) via the IVC and ADC.

The digital part contains the DSP and a control unit. The control unit is designed to manipulate the DSP to calculate the two vital signs, SpO2 and BPM. The DSP calculates the R value by using the current from the ADC, and then it calculates SpO2 using *R*, as mentioned in Section 2. It is also capable of controlling a liquid crystal display (LCD) for the vital signs, and transmitting them to a remote monitoring system by the RF transceiver. Finally, the RF part consists of a clock generator and a transceiver. The clock generator synchronizes the digital part and the transceiver supports wireless communications with an external monitoring system. If the sensor controller detects a change in the current value derived from the sensor using both reflected and absorbed light, the current value is transferred to the IVC and ADC. The current value is converted into a digital value, i.e. *R*, through a DSP via the IVC and ADC. Then, the DSP calculates both SpO2 and BPM using *R*. After that, the vital signs are either displayed on the LCD or transmitted through the RF transceiver to a smartphone using an RFID reader. Otherwise, if the sensor controller does not detect any change in the current value, our pulse oximeter just stays in an idle state.

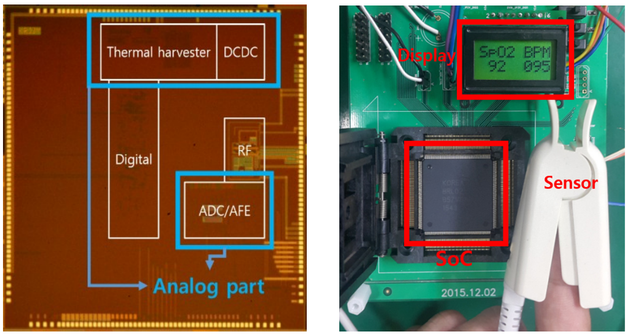
3.2 Design Optimization for Low Power Consumption

In order to reduce the power consumption of the pulse oximeter, we employ a custom sensor driver that is able to completely power off if it is not used. Also, we utilize a custom ADC that achieves high measurement accuracy and low power consumption [7]. The RF transceiver is designed to transmit data by changing the impedance of a tag without an additional power amplifier that consumes much power.

Furthermore, all the modules of the pulse oximeter, excluding the RF transceiver, are intended to be synchronized with a clock at 32.768 kHz. Different from the existing devices that operate at several tens of megahertz, our system is designed to operate on a single clock at a very low frequency. Therefore, our design achieves ultra-low power consumption compared to the existing ones.

4. Performance Evaluation

The design of our pulse oximeter was fabricated with Dongbu HiTek 0.11μm complementary metal-oxide semiconductor (CMOS) technology. Fig. 3(a) shows a die photo of the fabricated chip, and Fig. 3(b) presents a demonstration of measuring both SpO2 and BPM with the printed circuit board (PCB) that houses the chip. The area for the digital logic is 168,143 μm^2 and for the analog and RF logic, it is 100,393 μm^2. Also, the power consumption of digital and analog logic was measured as only 165.7 μW and 5.1 μW, respectively, at 0.8 V_{dd} . Table 1 shows a comparison of power consumption between our proposed device and conventional designs. Our design achieved almost 30% reduction in power consumption, compared to the customized ones. Although the MCU-based design seems to outperform our design in terms of power consumption, it is not appropriate to compare the two designs directly, since some functions of our pulse oximeter (including wireless data transmission) are not supported by the MCU-based design.



(a) Die photo of fabricated chip (b) PCB for the tests

Fig. 3. Chip implementation and verification.

Table 1. Comparison of power consumption.

	MCU-based [2]	Customized [3]	Our proposd
Power Cons. (@0.8 V_{dd})	Low (137.5 μW)	High (216.6 μW)	Low (165.7 μW)
Vital Signs	*SpO2*	*SpO2*	*SpO2, BPM*
Wireless Trans.	X	X	O
Certification	X	X	O

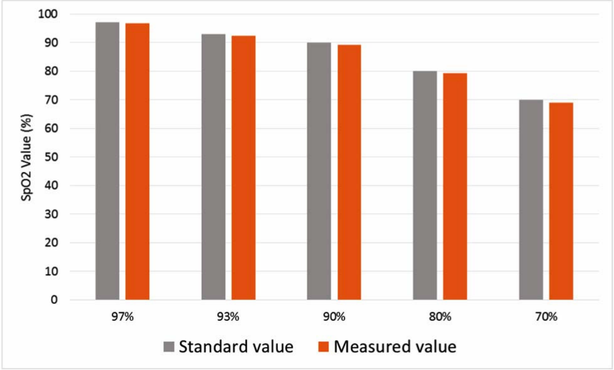


Fig. 4. Measurement accuracy for chip. The x-axis is the range of SpO2 values used in this measurement. The standard value is the SpO2 value of the simulator, and the measured value is the SpO2 value measured by our chip.

Verification of our system was performed by comparing the results of our device's measurement with that of a pulse oximeter tester. Thus, we found that our pulse oximeter accomplished high measurement accuracy. Fig. 4 shows the measurement accuracy. In detail, we connected the SpO2 simulator, an Oxitest Puls7 [8], to the sensor of our chip in order to test the accuracy. As a result, we obtained an average error rate of 2.3% and 1.4% for SpO2 and BPM, respectively.

5. Conclusion

In this paper, we proposed an ultra-low–power and remote observable pulse oximeter. We achieved considerable power reduction by 1) using a low-frequency single clock in all the modules, 2) employing both a customized sensor driver and an ADC, and 3) adopting RFID technology. In addition, our device was publicly certified by the Ministry of Food and Drug Safety in Korea, so it is possible to conduct clinical trials for commercial approval.

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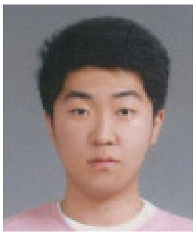

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