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An Integrated Photo-Plethysmography Recording Circuit for Trans-Nail Pulse-Wave Monitoring System

Zhengyang Qian[1], Yoshiki Takezawa[1], Kenji Shimokawa[2], Hisashi Kino[3], Takafumi Fukushima[1], Koji Kiyoyama[4] and Tetsu Tanaka [1,2]

[1]Dept. of Mechanical Systems Engineering, Graduate School of Engineering, Tohoku University
[2]Dept. of Biomedical Engineering, Graduate School of Biomedical Engineering, Tohoku University
6-6-12 Aza-Aoba, Aramaki, Aoba-ku, Sendai 980-8579, Japan
Phone: +81-22-795-6978, E-mail: link@lbc.mech.tohoku.ac.jp
[3] Frontier Research Institute for Interdisciplinary Sciences, Tohoku University
[4]Dept. of Electrical and Electronics Engineering, Nagasaki Institute of Applied Science

Abstract

To realize an unconscious and real-time pulse-wave monitoring in dairy living, we have proposed a trans-nail pulse-wave monitoring system which was placed on finger-nail to detect photo-plethysmography (PPG) signal as pulse-wave. In this paper, we designed an integrated PPG recording circuit which was composed of a 600x600-μm^2 photo-diode (PD), 2nd-order differentiator circuit, pulse width modulation (PWM) controller, current driver to light emitting diodes (LEDs), and 2-channel AC/DC signal readout circuit. The proposed circuit had a very small circuit area of 2.2mm × 1.1mm designed with 0.18μm CMOS technology. The proposed circuit was placed on the nail and electrical characteristics was measured precisely. As a result, the PPG waveform was obtained successfully.

1. Introduction

Since a PPG is non-invasively recorded in real-time, the PPG signal can be easily used for other applications such as disease screening, diagnosis, patient follow-up, and health control. Therefore, various types of wearable PPG sensors such as ear-hook reflection sensor and ear clip transmission sensor have been developed [1-2]. In the conventional PPG recording, optical source (e.g. LEDs) emits light into subcutaneous tissues including vessels and bones through skin. Then, optical signals are partly absorbed, transmitted to another side, and reflected from the tissues. In this process, as the transmitted and reflected optical signals vary regularly in accordance with an arterial blood volume during systole and diastole of heart, we can measure the heart rate (HR) by the time difference between peaks. The oxygen saturation level (SpO_2) can be estimated by the ratio of AC and DC components in infrared and red optical signals. Other information like blood pressure is available with speed-wave and acceleration-wave of PPG [3-4].

In this paper, we have proposed a trans-nail pulse-wave monitoring system to measure reflected light or transmitted light via the nail. Since human's fingernail has no sweat glands unlike finger-tips and wrist, the PPG signals can be effectively recorded via the nail. We focused on the design and electrical evaluation of an integrated PPG recording circuit.

2. PPG Circuit Design of Pulse-Wave Monitoring System

Fig. 1 shows a conceptual configuration of the trans-nail pulse-wave monitoring system and a schematic diagram. In the system, CMOS IC, a wireless chip, and LEDs are assembled on the nail-size PCB board using chip-stacking technology. We designed the PPG recording circuit including LED driver (I-source), PWM circuit for LED control, ring-oscillator (RING) with ultra-low oscillation frequency of 0.17Hz, a PD as detector of optical signals, regulator (LDO) for lowering the battery voltage from 3.3V to 1.8V, current-to-voltage (I/V) converter, low noise amplifier (LNA) with 4 gain levels of 20, 26, 32, and 40dB, low pass filter (LPF) with variable cut-off frequencies, 2-order differentiator (2-order Diff), buffer amplifier (BA), and 12bit SAR type analog-to-digital converter (ADC) for the PPG readout front-end.

Fig. 2 shows a LED driver circuit diagram. To implement a circuit operating at very low frequency in the '1-Chip' section, we used Ring-OSC circuit to generate a 0.17Hz pulse. Then, we added 2 pulses to an AND gate circuit from Ring-OSC and PWM circuits, respectively. The output of the AND gate became the switch signal of I-source. I-source circuit can generate a LED forward current of 20mA for 3 color LEDs of green, red, and infrared (IR). In the PWM circuit, the charging and discharging of capacitor by 300-nA I-sources with S1 and S2 can be controlled by Vr, Vth, V_L and V_H (changed from 0.2V to 1.4V), which leads to changing the V_{out} between high and low with a peak signal frequency of 20kHz. Duty-cycle can be altered by V_L and V_H in the ranges between 0.25%~99.75% with changing V_L and V_H. The ring-oscillator can oscillate with 0.167Hz and 33% duty cycle. As shown in Fig. 3, the LED emitted optical signals with the same frequency as the PWM output frequency only when the outputs of ring-oscillator became high.

3. Experimental Results

The proposed PPG recording circuit was fabricated by a 1-Poly 5-Metal 0.18-μm CMOS technology. The die microphotograph was shown in Fig. 4. Total area of the PPG recording circuit was 2.42 mm^2.

To verify the PPG readout circuit, we operated the circuit to detect PPG signals through the fingernail. Both the LED and chip were placed on the finger-tip. We used the circuit front-end composed of I/V converter, LNA, LPF, and BA in the measurement. Fig.5 shows the PPG waveform obtained from the measurement. Due to heart-beating, blood-flows in the fingernail varied periodically. In the measured waveform, crest parts indicated that the heart pushed blood back into artery. In this result, there were 3 crests during 2 seconds, then we obtained the HR of almost 90 bpm.

4. Conclusions

We designed the PPG recording circuit including the LED driver and photo-diode. From the comparison with other PPG recording circuits summarized in Table.1, we realized the smaller-size PPG recording circuit and successfully measured the PPG signal from the fingertip via the nail. In further works, we will stack the PPG recording circuit with LEDs and assemble those with the wireless chip to realize an unconscious and real-time pulse-wave monitoring in dairy living.

Acknowledgments

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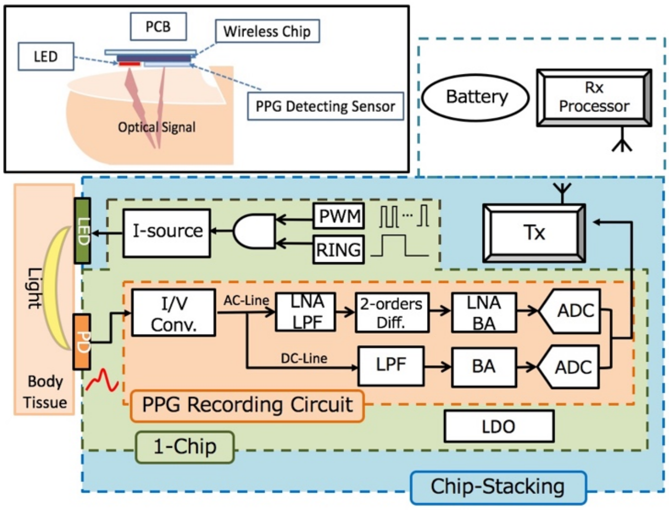

Fig. 1 Conceptual drawing and block diagram of Trans-Nail Pulse-Wave Monitoring System.

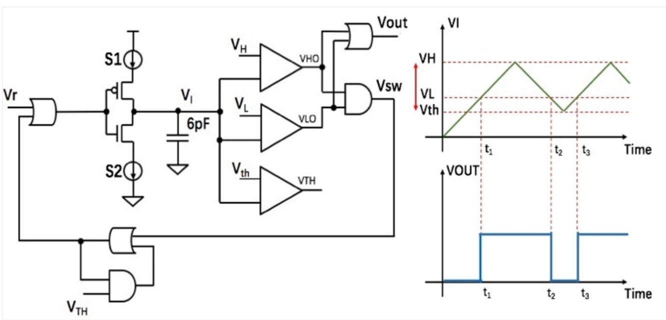

Fig. 2 Schematic and signal diagram of PWM circuit for LED controller.

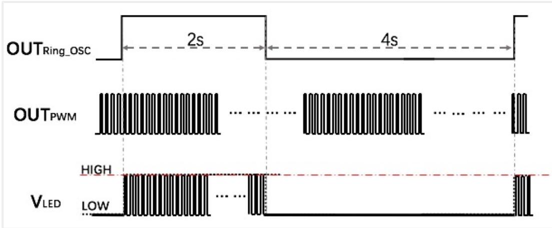

Fig. 3 Time diagram for LED driving.

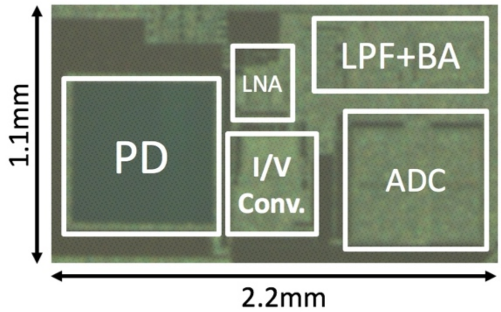

Fig. 4 Photograph of PD and PPG readout circuit.

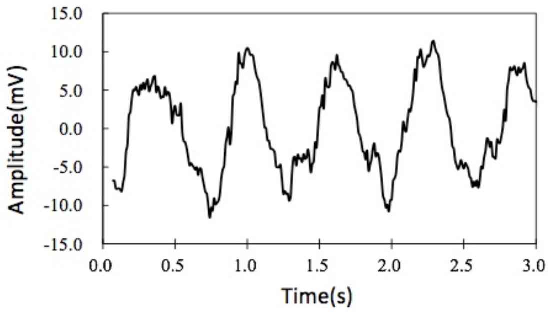

Fig. 5 PPG measurement result from human fingertip.

Table. 1 Comparison of circuit features.

	This work	Ref. [5]	Ref. [7]
Process (μm)	0.18	0.18	0.18
Active area (mm^2)	1.43	1.84	6.61
Integrated function	2-orders Differentiator	None	Motion noise rejection
LED duty cycle (%)	0.25~99.75	0.7	2~25

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