A Low-Power Dynamic-Range Relaxed Analog Front End for Photoplethysmogram Acquisition*

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***Abstract*—This paper presents a low-power analog front-end that enables photoplethysmographic signals acquisition, the dynamic range for AC component exaction is relaxed with simple high-pass implementation. The chopping modulation ensures the low-noise operation. The circuit is fabricated in a 0.18-um CMOS technology. Measurements show that the consuming current is approximately 72 uA at a supply of 2.5 V. The circuit achieves a input noise of 6.45 pA/$\sqrt{Hz}$. The calibred algorithm is implemented by means of MCU, and the demonstration that is compared with the Fluck Simulator used as the reference shows the heart rate is accurately detected, and the error of the measured blood oxygen saturation is less than 1.5%.**

I. Introduction

Pulse oximetry is widely used for measuring photoplethysmographic(PPG) signal and oxygen saturation(S_pO_2) in wearable biomedical application as it is safe, convenient and noninvasive, the implementation is using an infrared(IR) light and a red(R) light sources that illuminate the target object and a photodiode(PD) that captures the reflected light. The analog front end(AFE) for implementing the plus-oximeter system usually consists of two blocks[1], one is the transmitter(TX) that is the LED driver, another is the receiver(RX) that comprises the PD and the transimpedance amplifier(TIA). To save the chip power dissipation, the LEDs(IR and R) are usually pulsed at a fixed pulse repetition frequency(PRF). The produced PPG signal represents the light that has been absorbed by the finger and is divided in a large DC component and a much smaller AC component. The frequency of AC component gives heart rate(HR), and S_pO_2 can be calculated according to the AC/DC values resulting from R and IR. Hence, the receive channel with high dynamic range is required to enable HR and S_pO_2 measurement. The noise performance of the photodiode dc bias is also critical since its noise is directly injected at the input of the front-end receiver. Another issue in RX design is the elimination of the ambient contribution in DC component, which enables dynamic range(DR) enhancement..

To address these concerns, [1] consumes significant power to guarantee a wide enough readout dynamic range. A high-pass function in TIA is performed through an error amplifier in feedback to remove the ambient [2], which also eliminates the DC portion and is just used for the PPG measurements. A logarithmic amplifier is implemented to increase the dynamic range [3], this operation increases complexity. [4] removes static interferers by using a digital feedback loop, while the implementation consumes a large power. In [5], both AC and DC signals are tackled in the digital processing domain. In order to boost the DR, a current DAC in a feedback configuration is commonly used for the implementation of the ambient compensation [1], [4], [6], [7], which adds implementation complexity, size and power dissipation.

To solve these problems aforementioned, a low-power pulse oximeter AFE is proposed in this work. The relaxation of dynamic range requirement is realized without using DAC implementation, which simplifies the design, then saves the power and area consumption, and the circuit also achieves a low input noise.

II. Procedure for Paper Submission

Fig. 1 shows the block diagram of proposed pulse oximeter system, the AFE communicates with an external MCU. The RX channel consists of TIA, sampled and hold low-pass filter(S/H LPF), high-pass filter and variable programmable amplifier(VGA). A LED driver capable of driving dual LEDs enables both optical HR and S_pO_2 measurement, LED driver is controlled by an 8-bit DAC and a counter connected to MCU, which achieves the adjustment of the different LED currents. Additionally, the MCU has these functions as follows: digitalizing and filtering the signals, implementing PPG extraction and S_pO_2 calculation algorithm, and providing clocks($f_{Chopper}$ and f_{Timer}) for the operation of the analog blocks. In this work, the AC portion and DC portion of PPG signal are separated through a high-pass structure, then converted by ADC1 and ADC2, respectively. Such operation relaxes the DR requirement of RX channel, as discussed in next section.

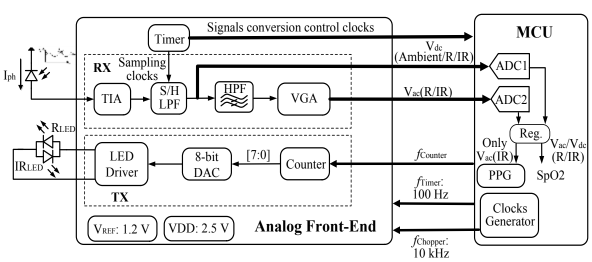

Figure 1 System block diagram of proposed pulse oximeter in this study.

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III. Circuits Implementation of AFE

A. Receiver Channel

The circuit of RX is shown in Fig. 2, the structure of TIA is a two-stage fold-cascode structure [8], the large open-loop gain ensures the accuracy of TIA. The output of TIA V_O can be expressed as

$$V_o = I_{ph} R_F, \tag{1}$$

where I_{ph} is the PD current, R_F is the transimpedance gain. Considering the junction capacitance of the photodiode, the value of the feedback capacitor C_F is carefully chosen to stabilize the TIA [1].

One important feature of the TIA is its DR that can be enhanced by increasing sensitivity, which means TIA must have lower noise. Hence, an additional chopping modulation is implemented to suppress the input noise and the input offset. The photocurrent pulses from the PD are converted to voltage by a TIA, then is demodulated using the switched capacitor(SC) filter. The low-pass corner can be given by [7]

$$f_{-3dB} = \frac{D}{2\pi R_L C_L}, \tag{1}$$

where D is the duty cycle of the sampling pulse. Thus the filter cutoff can be controlled by adjusting the width of the sampling pulse to further reduce any noise aliasing that occurs at the output of the TIA.

By using the clock modulation, TIA realizes two outputs: V_A and V_B. V_A is the output that includes both LED(R and IR) light signal and ambient light signal, while V_B is only the sampled ambient light signal, the separation is realized by using switched operation. Note that V_A is connected to a RC-filter that performs high-pass function and blocks DC signal, and the values of C_H and R_H determine the cutoff frequency. Then, the baseline wander is removed, and the AC component of PPG signal is coupled to VGA that is implemented with a non-inverting architecture, the output swing of VGA only needs to meet the gained AC signal requirement. Therefore, the output dynamic range of front-end receiver is relaxed.

B. Transmitter Channel

Fig. 3 shows the diagram of proposed TX circuit, which consists of LED driver, current DAC, and counter. Based on the H-Bridge structure [1], the LEDs can be alternately driven through the operation of the clocks f_r and f_{sw}, and the adjustable duty cycle of LED is achieved by changing the duty cycle of f_{sw}. In order to optimize the noise power performance of the driver output current, the differential pair of the two-stage fold cascode op-amp is chopped to remove low frequency noise. The LED current can be programmable by means of an 8-bit DAC plus an 8-bit counter controlled by the clock $f_{counter}$. The maximum value is up to 50 mA.

C. Timer Module

Fig. 4 illustrates the operation of the timing control in the AFE, all timing sequences are non-overlapping operation, f_{clkA} and f_{clkB} are implemented to sample the LED signals and ambient light signals, respectively. With the operation, the sampled LED signals and ambient signals are alternatively sent to MCU, as shown in Fig. 2. Since the two different LED Signals (I and IR) are alternatively generated, clocks f_{clk1} and f_{clk2}(f_{clk4} and f_{clk3}) used as the control signals for the ADC1 and ADC2 operation are implemented to control the converting process of two different ambient signals(LED signals). Such

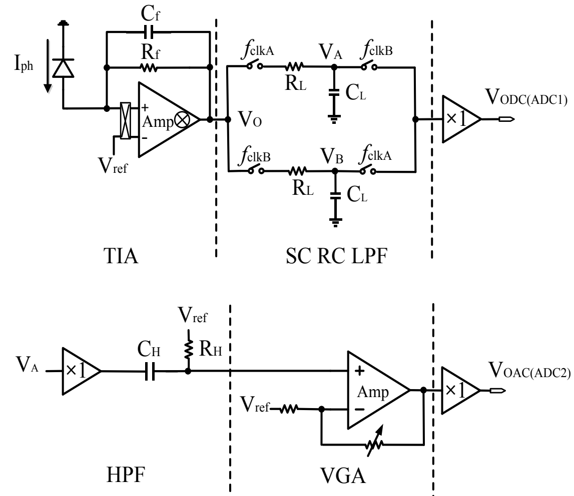


Figure 2 Circuits implementation of RX.

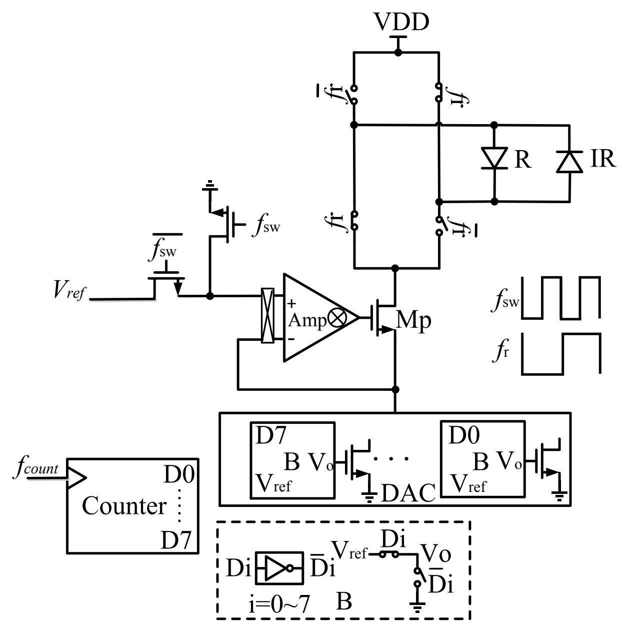


Figure 3 Circuits implementation of TX.

operation also ensures each converted data can be correctly recognized and processed in MCU.

IV. Measurements and Demonstrations

Fig. 5 shows the chip diagram of proposed AFE, and the external LEDs are utilized. An off-chip C_H of 2 nF is chosen to achieve a high-pass cutoff frequency of 0.5 Hz in this work, and the signal bandwidth is set to 10 Hz. Fig. 6 presents the test setup that estimates the performance of our proposed AFE used for monitoring HR and S_pO_2, the Fluck Simulator is used to provide the PPG signals for monitor, and a calibrated algorithm is implemented through the usage of MCU, the measured values are displayed by utilizing a LCD. LEDs are

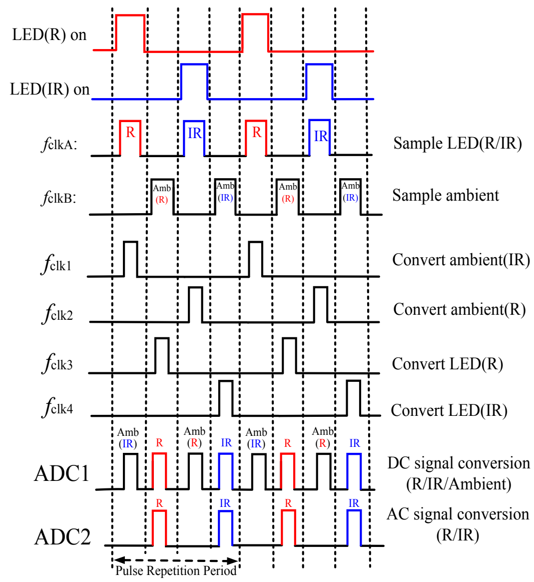


Figure 4 Timer program implemented in AFE

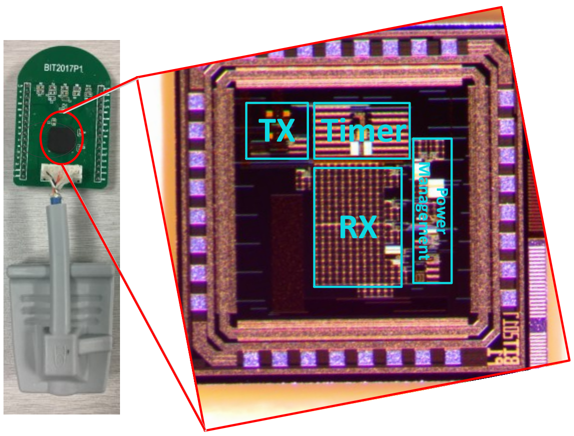


Figure 5 Chip micrograph of AFE

modulated by a frequency of 100 Hz, and the duty cycle is set to approximately 25%.

Fig. 7 illustrates the output waveforms of AFE, which also demonstrates the dynamic DC cancellation by using high-pass filter. V_A is the discrete PPG signal, V_{OAC} is the amplified AC component that is separated from VA. Both the DC and AC signals as the inputs are connected to MCU where two 12-bit ADCs are used to convert the different signals, Fig. 8 shows the operational performance in MCU, the AC component and DC component of different PPG signals are extracted. After calibrating our pulse oximeter, the measurements of HR and S_pO_2 are implemented, and the results are compared with the Fluke Simulator. Fig. 9 shows the measured performance, each data point reflects the average for five tests at each target, and each test is implemented for 30 seconds. Fig. 9(a) gives the measured HR when the input frequency of PPG signal is swept from 0.67 Hz-2.5 Hz. Fig. 9(b) presents the S_pO_2 measurement, the maximum standard error is less than 1.5%.

The experimental input current noise density is shown in Fig. 10, with the chopping modulation, the integrated value is approximately 6.45 pA(0.5 Hz-10 Hz).

Table I summarizes characteristics of our proposed AFE compared with other published state-of-the arts. The proposed circuit performs better in terms of power dissipation as well as input noise. Moreover, the dynamic DC component of PPG signal is eliminated without the complicated DAC operation.

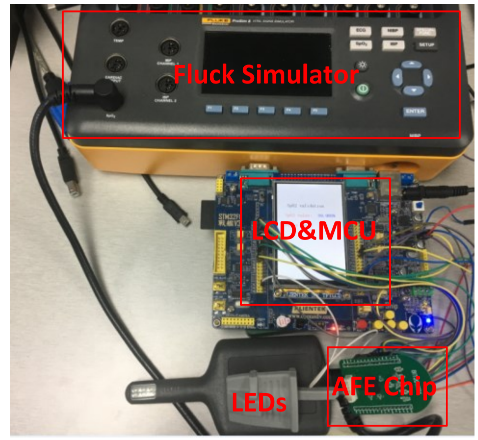


Figure 6 Test setup for proposed AFE.

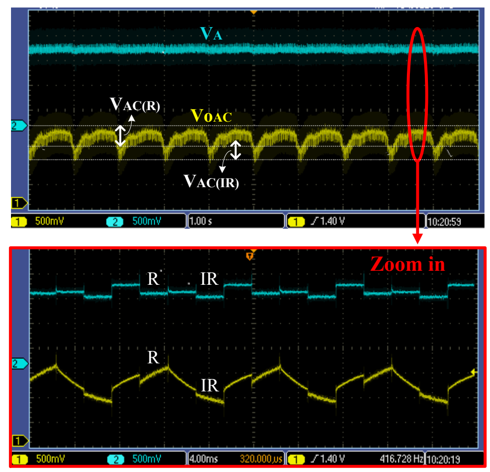


Figure 7 Experimental output waveforms of AFE.

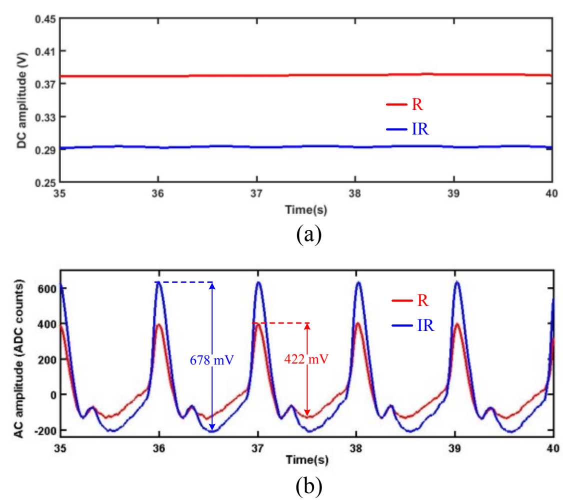
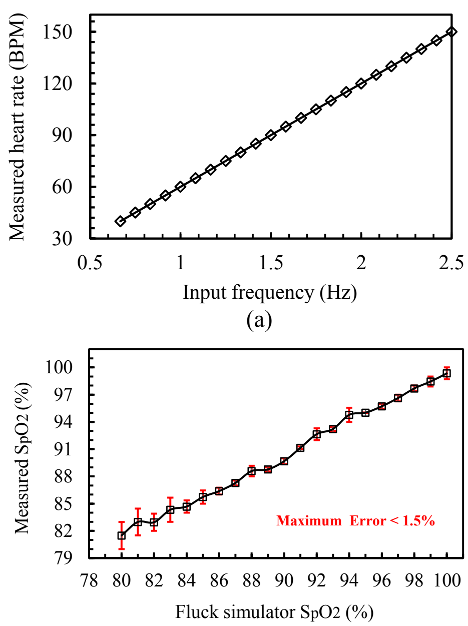


Figure 8 Calculated PPG signals in MCU:(a) DC portion; (b) AC portion.

TABLE I. COMPARISON WITH OTHER STATE-OF-THE-ART AFES FOR PPG ACQUISITION.

	This work	**[1]**	**[2]**	**[3]**	**[4]**	**[5]**	**[6]**	**[7]**
Process (µm)	0.18	0.18	0.35	1.5	0.35	0.18	0.18	0.13
Supply voltage (V)[a]	2.5	3.3	2.5	5	3.3	1.8	1.2	1.5
Supply current (V)[a]	72	600[b]	240[b]	80	160	120[c]	143[c]	45.8[c]
Integrated noise (*pArms*) Bandwidth (Hz)	6.45 10	3.2 20	2200 6	N/A	890 10	600 10	486 10	4 5
Sampling frequency (Hz)	100	100	100	100	100	165	128	100
R_f (Ω)	40k	500k	2k	N/A	500k	1M	50k	100k
LED peak current (mA)	50	100	N/A	15	7.1	25.6	0.036	50
LED duty cycle	25%	50%	10%	3%	4%	0.7%	N/A	20%
DAC implementation for DC cancellation	No	Yes	No	No	Yes	No	Yes	Yes
Application	HR & S_pO_2	HR & S_pO_2	HR	S_pO_2	HR & S_pO_2	HR & S_pO_2	HR	HR

a. Exclude LED and power management, b. only RX, c. include ADC



(b)

Figure 9. Demonstrated results: (a) heart rate; (b) S_PO_2

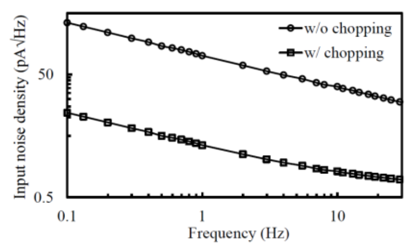


Figure 10. Experimental input noise density

V. CONCLUSION

In this work, a low-power AFE is implemented for the PPG signal acquisition. With high-pass operation, a simple solution for the separation of DC signal and AC signal is realized. Consequently, the dynamic range requirement of AFE for AC portion extraction is relaxed. By means of a calibration implemented in MCU, the proposed circuit has excellent performance in terms of heart rate and oximetry monitoring. The design can ensure a precise pulse oximeter front end for application in health caring systems.

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