A SAR-Assisted Zoom Light-to-Digital Converter with Fast Baseline Adaptation and Robust Low-PI PPG Acquisition

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***Abstract*—Wearable photoplethysmography (PPG) readouts are required to accurately resolve weak pulsatile AC signals under low-perfusion index (PI) and varying baseline/ambient-light conditions. This paper presents a zoom-style light-to-digital converter for wearable PPG sensors that targets both fast recovery from ambient-light-induced baseline shifts and high-fidelity low-PI acquisition. The proposed architecture combines a 5-bit SAR coarse quantizer with a 3rd-order continuous-time incremental delta-sigma modulator (CT-IDSM). The SAR stage rapidly locates the input signal range and adaptively recenters the fine IDSM quantization window in a zoom-style manner. Fabricated in 180-nm CMOS, the prototype shows a maximum input current of 122 μA and a dynamic range of 106.9 dB. An averaged power consumption of 15.4 μW is achieved at 125 Hz and 0.625% duty-cycle. The readout maintains PPG signal integrity under fast ambient-light-induced baseline transients. The readout also demonstrates stable AC-path SNR of over 40 dB across a 0.1%-1% PI range. These results prove the suitability for robust wearable PPG sensing demanding both rapid baseline adaptation and robust low-PI waveform acquisition.**

Keywords*—*photoplethysmography, light-to-digital converter, baseline adaptation, low perfusion index

I. Introduction

Optical physiological sensing techniques, particularly photoplethysmography (PPG), have been widely extended from clinical use to wearable health monitoring applications. Due to its non-invasive and low-cost nature, PPG is now integrated into wristbands, smartwatches, and smart rings for continuous physiological monitoring. Recently, wearable PPG systems have been increasingly explored beyond heart-rate and blood oxygen saturation (SpO_2) monitoring towards morphology-sensitive cardiovascular assessment, such as continuous blood pressure estimation and arterial stiffness analysis [1][2]. These emerging applications require not only detection of pulsatile signals, but also preservation of subtle waveform morphology under low perfusion, baseline variation, and environmental interference.

In wearable PPG systems, the photodiode (PD) receives both the desired optical signal and unwanted ambient-light interference. This results in a photocurrent consisting of a dominant DC component and a much smaller pulsatile AC component. A major difficulty in high-fidelity PPG acquisition is that the perfusion index (PI), defined as the ratio of the AC component to the DC component, can vary drastically across operating conditions. Ambient light can substantially increase the DC current, compress the available headroom for the AC signal, and even lead the front-end towards saturation, while lighting interference and other disturbances further attenuate the signal. In addition, as

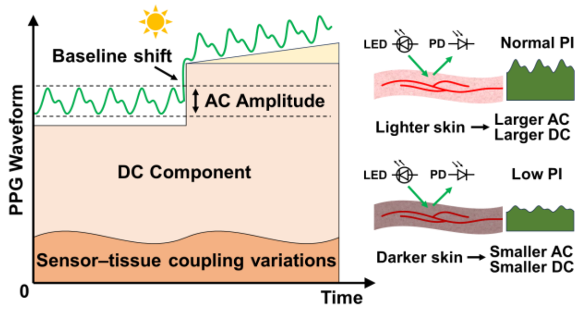


Fig. 1. PPG baseline shifts and PI variations.

illustrated in Fig. 1, darker skin tones attenuate the reflected optical signal and make low-PI operation more likely, whereas sensor–tissue coupling variations may simultaneously affect the DC baseline and AC amplitude[3].

From a circuit perspective, wearable PPG readout faces two coupled challenges: the front end must tolerate large and time-varying baseline/interference excursions without saturation, while still providing sufficiently high effective resolution for the weak AC component under low-PI conditions. This requirement is particularly stringent in morphology-sensitive applications, where preserving subtle waveform features may require about 10-bit effective AC resolution. Under extreme conditions such as strong ambient light and motion artifacts, the required total dynamic range (DR) can exceed 120 dB. To address these constraints, recent PPG readout research has shifted toward light-to-digital converters (LDCs), which directly digitize photocurrent and avoid the traditional transimpedance amplifier (TIA) to analog-to-digital converter (ADC) chain. Existing works mainly aim for wider DR and higher readout noise performance through different strategies, including coarse-fine quantization, low-power SAR conversion, noise shaping, and baseline cancellation. Li et al. [4] proposed a triple-slope LDC with coarse-fine zoom-style quantization, achieving 94.7-dB SNR and 136.5-dB DR. However, slope-based architectures inherently sacrifice conversion time for quantization precision, often requiring longer LED pulses for higher resolution and thus increasing system-level power consumption. To reduce power consumption, Gao et al. [5] presented a current-integration SAR-based LDC. While attractive for low-power operation, its AC quantization capability in low-PI scenarios is limited by the absence of noise shaping. Yao et al. [6] improved front-end noise efficiency through kT/C-noise suppression and multi-sample line fitting, achieving 119.4-dB DR, but its architecture does not explicitly address rapid baseline excursions under strong ambient-light conditions. Yao et al. [7] further introduced a hybrid-zoom readout that combines static baseline

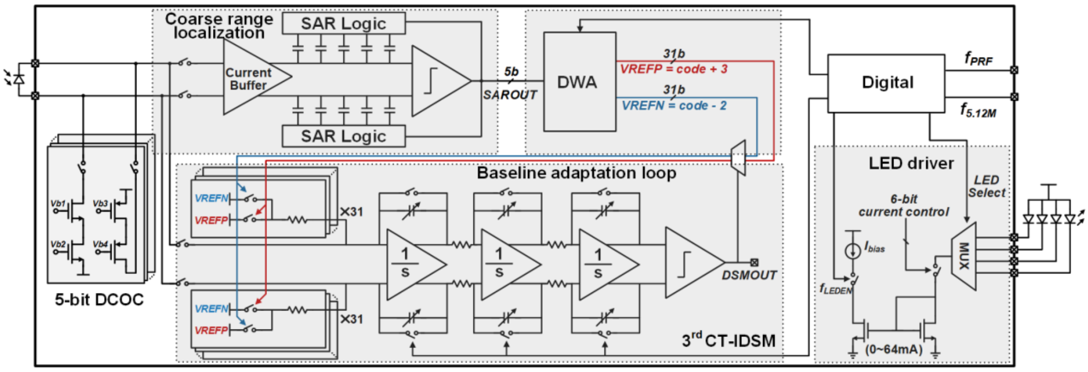


Fig. 2. Proposed system architecture.

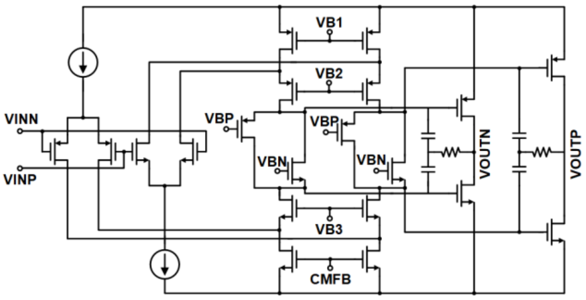


Fig. 3. Operational amplifier used in the IDSM.

cancellation with dynamic tracking based on a 2nd-order incremental delta-sigma modulator (IDSM), achieving 140-dB DR. Although this work explicitly addresses baseline variation, its tracking bandwidth remains limited, making the front end vulnerable to overload under rapid baseline transients. Therefore, what remains needed is a readout architecture that can quickly accommodate baseline fluctuations while still providing high-fidelity AC quantization under low-PI conditions for PPG morphology acquisition.

To address these limitations, this paper presents a SAR-assisted zoom-style light-to-digital converter that maintains high-fidelity PPG acquisition under varying PI and baseline conditions. The proposed architecture combines a 3rd-order continuous-time IDSM (CT-IDSM) for high-resolution AC quantization, with a 5-bit SAR-assisted baseline-adaptation loop that rapidly locates the input operating range and adaptively recenters the quantization window. While extreme conditions may challenge the total DR requirement, this work focuses on maintaining robust AC-path SNR and rapid baseline adaptation under moderate DR conditions.

II. System Design

Fig. 2 shows the proposed monolithic PPG chip architecture, consisting of a transmitter (TX) and a receiver (RX). The RX adopts a hybrid readout architecture comprising a 3rd-order CT-IDSM for fine current-domain quantization, a 5-bit SAR ADC for rapid coarse range detection, and a 5-bit DC offset cancellation (DCOC) module for extending the allowable input current range. The SAR ADC first identifies the approximate input operating range and adaptively updates the reference levels of the CT-IDSM, thereby recentering the fine quantization window before fine conversion. With coordinated timing between the SAR and the CT-IDSM, the proposed RX achieves coarse range localization followed by fine residual quantization.

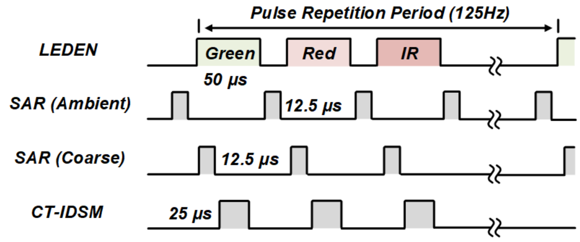
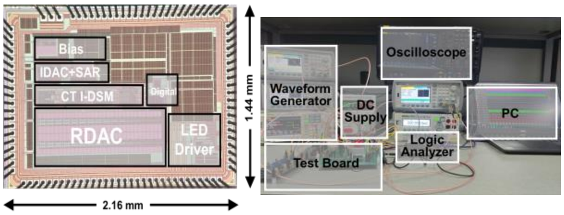


Fig. 4. Timing diagram of the proposed architecture.

The TX includes a 6-bit programmable LED driver with up to 64-mA output current and supports multi-channel time-division-multiplexing (TDM) operation for multi-wavelength PPG sensing.

Conventional wide-range LDCs quantize the full PPG signal range directly, so the limited quantization resolution is inefficiently allocated to the small pulsatile AC component. Although servo-loop-based ambient-light cancellation has been reported [8], its inherently low feedback bandwidth leads to long settling time, making the front end vulnerable to abrupt ambient-light-induced baseline shifts. Therefore, rather than forcing a single quantizer to simultaneously handle large-signal range adaptation and fine-signal digitization, the proposed zoom-style LDC separates these tasks into coarse operating-range localization and fine residual quantization with noise shaping. The 5-bit SAR completes coarse quantization within 12.5 µs, thereby rapidly identifying the approximate operating range of the input signal. Then the 5-bit SAR output is decoded into a 31-level thermometer-coded control word, which determines the allocation of the positive and negative reference segments in the IDSM resistive digital-to-analog (RDAC) feedback. The RDAC is divided into 31 parallel unit blocks. In the conventional full-range mode, the entire RDAC array participates in the DSM feedback. In the proposed zoom-style mode, only a subset of the RDAC segments is activated according to the SAR result, thereby recentering the fine quantization window around the detected operating point. An over-ranging margin of 5 LSBs is reserved to maintain the DSM loop stability. For example, with a SAR output of 10, 13 positive-side and 8 negative-side segments of the RDAC are activated. In addition, data-weighted averaging (DWA) is applied to improve DAC linearity.

Under low-PI conditions, the pulsatile AC component becomes extremely weak, demanding high-resolution quantization to preserve waveform fidelity. The proposed 3rd-order CT-IDSM is therefore used to finely quantize the local residual signal after coarse range localization. Since the



(a) (b)

Fig. 5. (a) Chip micrograph and (b) Measurement setup.

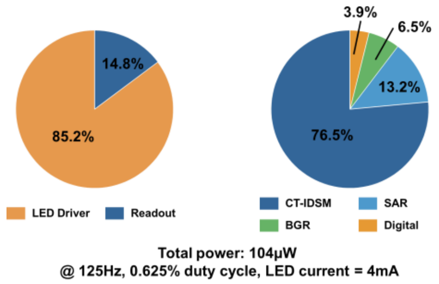


Fig. 6. Chip power breakdown.

LEDs are driven in a duty-cycled and time-multiplexed manner, the readout channel must also operate in a pulsed method to process photocurrent from different wavelengths sequentially. Accordingly, the modulator is operated in incremental mode rather than continuous free-running mode. The class-AB operational amplifier (Fig. 3) is used here to ensure sufficient in-band gain and input range requirement for the high-resolution conversion. Although the 3rd-order structure consumes the most power, it is still acceptable at the duty-cycle mode.

Ambient-light cancellation is conventionally performed by double sampling [4]. However, repeated front-end sampling increases the active time and power consumption. In the proposed readout, ambient-light estimation is assigned to the 5-bit SAR ADC, since the coarse measurement is sufficient and the ambient light does not require the same resolution as fine signal quantization. This also reduces power consumption because the SAR stage is significantly more energy-efficient than the DSM loop. As the timing diagram in Fig. 4 shows, each conversion cycle starts with the LED turned off, during which the SAR ADC samples the ambient-light baseline. After the ambient sample is stored, the LED is turned on and the SAR ADC performs coarse range localization. The SAR result is then used to configure the CT-IDSM reference levels, after which fine incremental conversion is started. The CT-IDSM uses an oversampling ratio (OSR) of 128. At a sampling frequency of 5.12 MHz, the fine conversion is completed within 25 µs, leaving the remaining portion of the 125-Hz pulse-repetition period for reset and power saving. As a result, the LED only remains on during SAR-based range detection and IDSM conversion, thereby significantly reducing TX power consumption. Therefore, for each PPG samples, one ambient sample before the LED-on sample and another one after are acquired. The clean PPG signal is then reconstructed off-chip by subtracting the average of the two ambient samples from the LED-on sample.

III. Measurement Results

The prototype chip was fabricated in a 180-nm CMOS process, occupying an active area of 3.11 mm^2. Fig. 5 shows

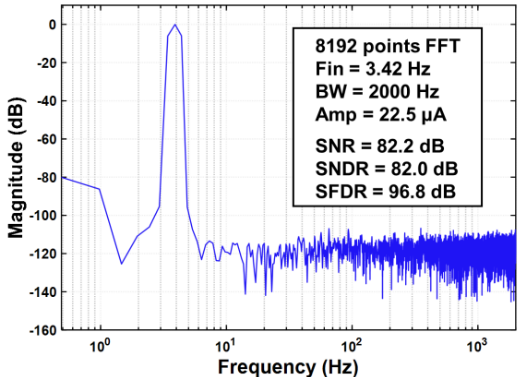


Fig. 7. Power spectrum density of the 3rd CT-IDSM.

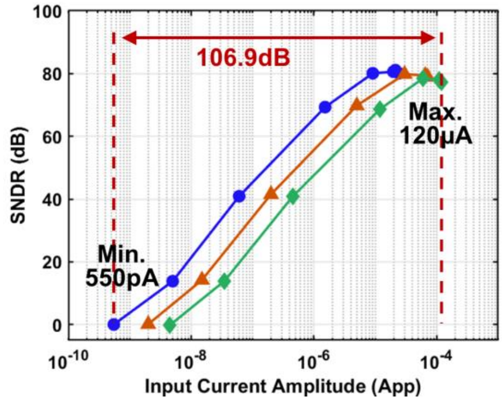


Fig. 8. Cross-scale dynamic range measurement results.

the chip micrograph and the measurement setup. Fig. 6 illustrates the measured power breakdown. The chip consumes a total power of 104 µW at a PRF of 125 Hz and 0.625% duty cycle. While the LED driver consumes the most power, The readout channel consumes about 15.4 µW under duty-cycled operation.

Fig. 7 shows the measured output spectrum of the IDSM for a sinusoidal input of 22.5 µA at 3.42 Hz. The readout achieves a maximum SNDR of 82 dB within a 2-kHz bandwidth. When the evaluation bandwidth is reduced to 20 Hz, the measured SNDR increases to 95.5 dB. Fig. 8 presents the measured cross-scale dynamic-range results. With the DCOC DAC enabled, the maximum measurable input current reaches 122 µA, and the dynamic range is extended to 106.9 dB.

To validate practical PPG acquisition, the commercial PD/LED module SFH7060 was used for finger PPG measurement. A 530-nm green LED was driven by the on-chip LED driver. The sensor was first placed in a dark environment with nearly no ambient light, and then a flashlight was used to generate a sudden ambient-light step. As shown in the Fig. 9, the ambient-light step causes an abrupt increase in the signal, while the SAR-assisted adaptation loop helps the PPG waveform recover and maintain signal integrity.

Fig. 10 shows the AC-path SNR stability across varying PI and DC-current conditions. For this test, an equivalent PPG-like input was applied, consisting of a sinusoidal AC component added on a DC level. It should be noted that the AC-path SNR reported here is evaluated differently from the

TABLE I. COMPARISON WITH THE STATE-OF-THE-ART

	JSSC'24 [4]	TCAS-I'25 [5]	ESSERC'25 [6]	JSSC'25 [7]	**This Work**	
Technology	55 nm	180 nm	28 nm	180 nm	**180 nm**	
Supply Voltage (V)	1.8 / 3.3	1.8 / 3.3	1.8	1.2	**1.8 / 3.3**	
Area (mm^2)	4.59	2.4	1.96	0.52	**3.11**	
Bandwidth (Hz)	20	20	480	20	**2000**	**20**
SNDR (dB)	94.7	77.2	N. A	104	**82**	**95.5**
Readout Power /ch. (µW)	30	9.84	3880	12.5	**15.4**	
Max. Input (µA)	330	460	0.71	230	**122**	
Dynamic Range (dB)	136.5	148.9	119.4	140	**106.9**	
Baseline Adaptation	No	No	No	Yes	**Yes**	
PI Robustness	No	No	No	No	**Yes**	

conventional sinusoidal-input SNR used in prior work.

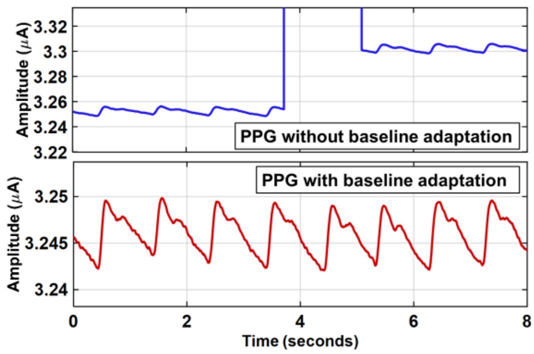


Fig. 9. PPG waveform and baseline adaptation measurement.

Specifically, the total spectral energy integrated over the PPG band from 0.5 Hz to 20 Hz is treated as signal power, while the remaining spectral energy is treated as noise. In the measurement, the DC amplitude was first fixed at 10 µA, while the AC current was swept from 10 nA to 100 nA (PI from 0.1% to 1%). Then the DC current was increased to 100 µA and the AC is also changed according to different PI. The results show that even when the PI decreases to 0.1% or the DC current increases to 100 µA, the AC-path SNR remains over 40 dB, which is stable for practical use.

IV. COMPARISON AND CONCLUSION

Table I summarizes the comparison between the proposed chip and state-of-the-art PPG work. The proposed readout channel achieves a cross-scale dynamic range of 106.9 dB with an average readout power consumption of 15.4 µW under duty-cycled operation. To the best of our knowledge, this work is the first to demonstrate stable AC-path SNR across a 0.1%–1% PI range in a wearable PPG readout.

In summary, the proposed PPG readout chip combines a 3rd-order incremental delta-sigma modulator for high-fidelity AC quantization with a 5-bit SAR-assisted loop for rapid baseline adaptation. The proposed architecture accommodates abrupt ambient-light-induced baseline shifts and maintains robust AC-path SNR across a wide range of PI and DC-current conditions. Together with the configurable multi-channel LED driver, the chip is well suited for multi-wavelength wearable PPG sensing, including not only heart-rate and SpO_2 monitoring but also morphology-sensitive cardiovascular analysis.

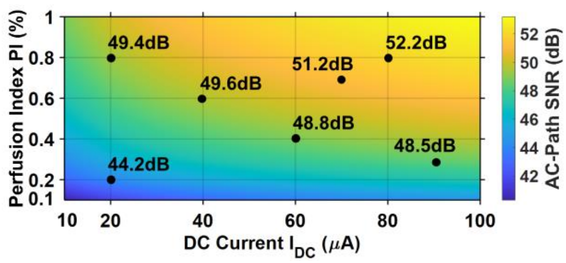


Fig. 10. AC-path SNR measurement under different PI conditions.

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