

Application Note

Analog Front End for Heart Rate Monitor

AN-CM-307

Abstract

This application note describes the design procedure of an analog front end for a heart rate monitor. The circuit utilizes a commonly used technique of measuring the green light reflected from skin. A unique Auto-Trim feature of the SLG47004 allows achieving stable circuit operation in various conditions. The application note also contains test results of a hardware prototype.

This application note comes complete with design files which can be found in the References section

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1 Terms and Definitions

AFE	Analog front end
ECG	Electrocardiogram
HR	Heart rate
IC	Integrated circuit
OpAmp	Operational amplifier
S&H	Sample and hold
TIA	Transimpedance amplifier

2 References

For related documents and software, please visit:

[AnalogPAK™ | Renesas](#)

Download our free GreenPAK Designer software [1] to open the .gp files [2] and view the proposed circuit design. Use the GreenPAK development tools [3] to freeze the design into your own customized IC in a matter of minutes. Find out more in complete library of application notes [4] featuring design examples as well as explanations of features and blocks within the AnalogPAK IC.

- [1] [GreenPAK Designer Software](#), Software Download and User Guide
- [2] [AN-CM-307 Analog Front End for Heart Rate Monitor.gp](#), GreenPAK Design File
- [3] [GreenPAK Development Tools](#), GreenPAK Development Tools Webpage
- [4] [GreenPAK Application Notes](#), GreenPAK Application Notes Webpage
- [5] SLG47004, Datasheet

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3 Introduction

Heart rate is one of the critical vital signs in humans. The monitoring and tracking of heart rate (HR) is a relatively simple task for modern electronics. That's why modern wearable devices like smartwatches and activity trackers widely utilize a HR monitoring function. In addition, such devices can detect possible diseases like tachycardia (fast HR), bradycardia (slow HR), arrhythmia (often changed HR), and others.

Also, HR monitors are widely used in sports. With the help of an HR measurement, athletes can define appropriate load and rest intervals.

4 Heart Rate Monitoring Techniques

There are several different techniques of how heart rate can be monitored. All these techniques use different types of signals.

4.1 Phonocardiography

This technique uses the sound signal produced by opening and closing of heart valves. As a rule, the signal is filtered and processed with the help of DSP. After proper filtering, it's possible to detect not only heart rate, but also abnormalities of the heart.

4.2 Pressure Sensing Technique

This technique utilizes a signal from a piezo sensor attached to one of the defined places on the human body, for example, on the wrist. Contraction and relaxation of the heart cause a corresponding change of pressure in the blood vessels.

4.3 Electrocardiography

This technique is based on the measurement of the electric field produced by the heart. There must be two or more electrodes placed on specific points of the human body. Graphic representation of ECG consists of six peaks and valleys called P, Q, R, S, T, and U. The heart rate is measured by averaging RR interval between two R peaks (Figure 1) over a defined period (for example, 15, 30, or 60 seconds).

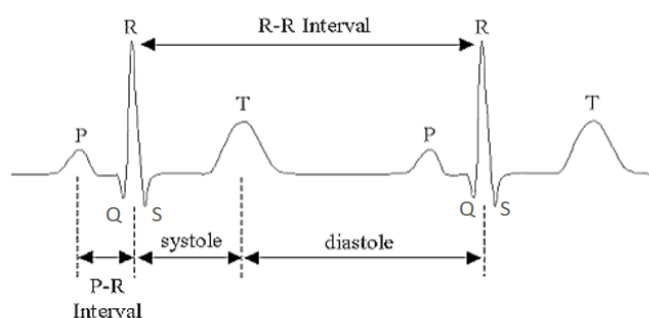


Figure 1: Typical ECG of Healthy Heart

4.4 Photoplethysmography

This technique is based on the measurement of the volume variations of light reflected from the skin. When light emitted from a LED passes through a blood vessel, the received light has pulsations that correspond to heartbeat. Typically, a green or infrared LED is used as a light source because of the characteristic of bloods' absorption to light with specific wavelengths. This technique is the most common way of heart rate monitoring in wearables.

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The most appropriate wavelength of green light for photoplethysmography is in the range from 540 nm to 570 nm. But as a rule, the LEDs with 530 nm are used, due to the high value of luminous intensity.

5 Proposed Design of Analog Front End

The proposed analog front-end circuit is shown in Figure 2.

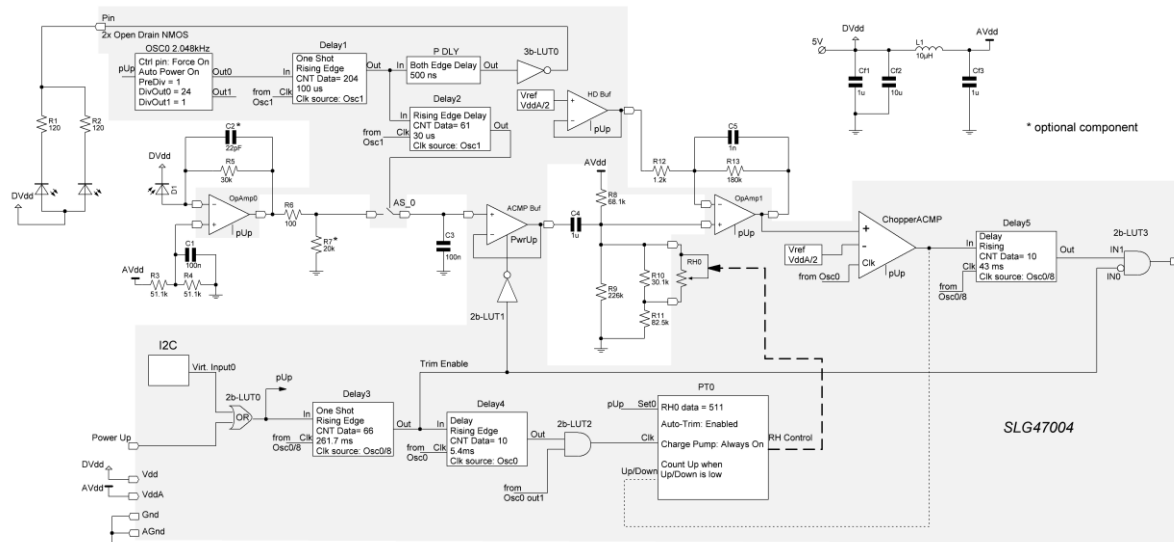


Figure 2: Analog Front-End Schematic

The circuit consists of the following parts: LED driver, transimpedance amplifier (TIA), sample and hold circuit, high pass filter, offset correction circuit, biased non-inverting amplifier, analog comparator with digital filter, and analog power supply filter. The structure of the proposed design is shown in Figure 3.

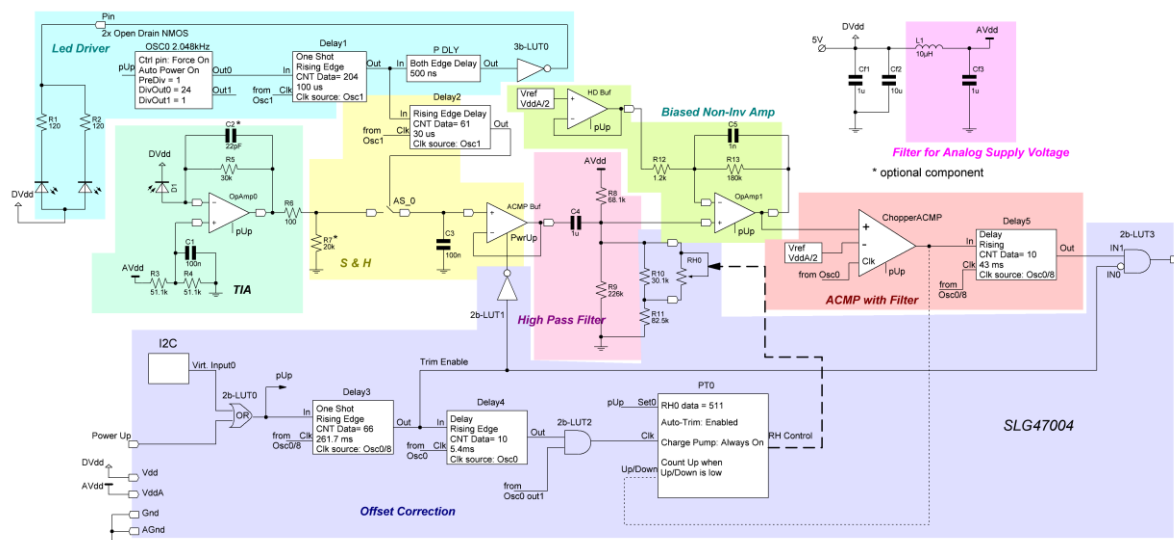


Figure 3: Analog Front End Structure

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5.1.1 LED Driver

The LED driver periodically turns on/off two green LEDs. The period is 11.7 ms (85.3 Hz). Turn on time duration is 100 μ s. So, the duty cycle is $0.1/11.7 = 0.85\%$. The operating current through each LED is 12.5 mA, giving 25 mA through one pin of the SLG47004. The average current through the pin is 213 μ A.

5.1.2 Transimpedance Amplifier

In this example the TIA operates in photovoltaic mode to convert small photodiode current to voltage. The photodiode part number is BPW34. It's possible to use other LEDs or photodiode, but in that case gain resistor R5 must be changed to provide an appropriate voltage level at the output.

Optional capacitor C2 increases the stability of the TIA. It's recommended to place C2 in case of stability issues of the TIA stage. The value of C2 can be calculated using the following formula:

$$C_f = \sqrt{\frac{(C_D + C_{CM} + C_{Diff})}{2\pi \cdot GBWP \cdot R_f}}$$

where C_D , C_{CM} , C_{Diff} - are diode capacitance, common-mode operational amplifier capacitance, and differential mode operational amplifier capacitance;

GBWP - is gain-bandwidth product of operational amplifier;

R_f - is the feedback resistor.

According to the datasheet, amplifiers of the SLG47004 have $C_{CM} = 7$ pF and $C_{Diff} = 8$ pF. Capacitance of photodiode $C_D = 40$ pF. GBWP = 512 kHz (setting) and $R_f = 30$ k Ω . So $C_f = 23.9$ pF or 22 pF (nearest standard value).

5.1.3 Sample and Hold Circuit

The S&H circuit consists of an analog switch, capacitor, and buffer. Sampling begins after 30 μ s pause when LEDs are turned on, see [Figure 15](#). During the pause, the output of the OpAmp is stabilized. When the analog switch is opened (sampling phase), the sampling capacitor C3 is charged to the voltage level at OpAmp0 output. The duration of the sampling time is 70 μ s.

During the hold phase the analog switch is closed. The sampling capacitor is disconnected from OpAmp0.

The buffer (ACMP buffer) eliminates the effect of the high pass filter on the sampling capacitor.

5.1.4 High Pass Filter

The first order high pass filter has a cutoff frequency of 2.3 Hz. The DC component of the signal after that filter is $V_{DD}/2$ V.

5.1.5 Offset Correction Circuit

The correction of amplifier and buffer offset voltages is implemented by changing the resistance of one branch of the voltage divider (R9, R10, R11, and digital rheostat RH0). The configuration of the divider gives the ability to trim the system with 100 mV accuracy (worst case) of the output voltage. The divider can be simplified if high accuracy isn't required.

5.1.6 Biased Non-Inverting Amplifier

The non-inverting amplifier has a gain of 151 and a bias voltage of $V_{DD}/2$ (2.5 V for $V_{DD} = 5$ V).

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5.1.7 Analog Comparator with Digital Filter

Digital filtering of the signal is performed by Delay5, configured as rising edge delay.

5.1.8 Analog Power Supply Filter and Grounding Considerations

A common practice for mixed-signal circuits is to provide analog supply voltage filtered from the noise generated by the digital part of the schematic. In the current project this is done with the help of an L-C filter.

Special care must be taken when routing the ground traces. Analog and digital grounds should be connected at one point. The resistance of the trace from the common ground to the power supply source should be as minimal as possible. Also, it's recommended to use a power supply source with low output impedance.

6 Internal Blocks Configuration

6.1 OpAmp0 and OpAmp1 Configurations

OpAmp configurations are shown in [Figure 4](#).

Mode:	OpAmp mode
Bandwidth Selection:	128 kHz
Charge Pump Disable:	Enable CP
Supporting Blocks On/Off:	Follows OpAmp
Vref connection:	to IN-
Vref:	VDDA * (32 / 64)

Figure 4: Operational Amplifier 0, 1 Settings

6.2 Chopper ACMP Configuration

Chopper ACMP configuration is shown in [Figure 5](#).

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Chopper ACMP	
OUT polarity:	Non-inverted (OU' ▾)
IN- Vref source:	OpAmp0 Vref (2.0' ▾)
Auto-Trim Channel:	Channel0 ▾
Channel 0	
IN+ CH0 source:	OpAmp1 OUT ▾
IN- CH0 source:	32/64 VDDA ▾
CH0 clock:	OSC0 ▾
Channel 1	
IN+ CH1 source:	InAmp OUT ▾
IN- CH1 source:	Ext. Vref (PIN 18 (G ▾
CH1 clock:	Ext. Clk. (From mat ▾

Figure 5: Chopper ACMP Settings

6.3 HD Buffer Configuration

HD Buffer shares the internal voltage reference with OpAmp0 macrocell. Note that in the current project internal Vref is disconnected from the OpAmp0. The power-up source for HD Buffer is the connection matrix signal. The HD Buffer and OpAmp0 Vref configurations are shown in Figure 6.

HD Buffer	VREF OPAMP0
Power up source: From matrix ▾	Enable selection: From register ▾
Power up register: Enable ▾	Register enable: Vref enable ▾
Connections	
Output: PIN 20 (GPIO6) ▾	Input voltage selection: VDDA ▾
	Output selection: VDDA * (32 / 64) ▾
	LPF enable: Enable ▾

Figure 6: HD Buffer and OpAmp0 Vref Settings

6.4 ACMP Buffer Configuration

To use ACMP buffer as a voltage follower, the ACMP1 and Vref1 macrocells should be configured as shown in Figure 7:

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A CMP1L		VREF1	
Hysteresis:	-	Power down source:	From matrix
IN+ gain:	Disable	Power down register:	Disable
Input LPF:	Disable	Force bandgap on:	Enable
Output LPF:	Disable	Source selector:	A CMP1L reference
Low power start up:	Disable	Connections	
Sampling mode:	Disable	Output:	
Vrefs source selection:	VDDA	PIN 15 (GPIO1)	
Connections			
IN+ source:	TEMP SENSOR out		
IN- Low to High source:	Ext. Vref (PIN 12 (G		
IN- High to Low source:	Ext. Vref (PIN 12 (G		
Information			
Typical ACMP thresholds			
V_IH (mV)	V_IL (mV)		
-	-		

Figure 7: ACMP1L and Vref1 Settings

6.5 Oscillators Configurations

Oscillator1 uses default settings. Oscillator0 configuration is shown in Figure 8.

OSC0	
Control pin mode:	Force on
OSC power mode:	Auto Power On
Clock selector:	OSC
'OSC0' frequency:	2.048 kHz
'CLK' predivider by:	1
'OUT0' second divider by:	24
'OUT1' second divider by:	1

Figure 8: Oscillator0 Settings

6.6 Delay Macrocells Configurations

Delay configurations are shown in Figure 9.

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8-bit CNT1/DLY1 (MF1)	8-bit CNT2/DLY2 (MF2)	8-bit CNT3/DLY3 (MF3)	8-bit CNT4/DLY4 (MF4)	8-bit CNT5/DLY5 (MF5)
Multi-function mode: CNT/DLY	Multi-function mode: CNT/DLY	Multi-function mode: CNT/DLY	Multi-function mode: CNT/DLY	Multi-function mode: CNT/DLY
Mode: One shot	Mode: Delay	Mode: One shot	Mode: Delay	Mode: Delay
Counter data: 204 (Range: 1 - 255)	Counter data: 61 (Range: 1 - 255)	Counter data: 66 (Range: 1 - 255)	Counter data: 10 (Range: 1 - 255)	Counter data: 10 (Range: 1 - 255)
Pulse width (typical): 100.098 us Formula	Delay time (typical): 30.2734 us Formula	Pulse width (typical): 261.719 ms Formula	Delay time (typical): 5.37109 ms Formula	Delay time (typical): 42.9688 ms Formula
Edge select: Rising	Edge select: Rising	Edge select: Rising	Edge select: Rising	Edge select: Rising
DLY IN init. value: Bypass the initial	DLY IN init. value: Bypass the initial	DLY IN init. value: Bypass the initial	DLY IN init. value: Bypass the initial	DLY IN init. value: Bypass the initial
Output polarity: Non-inverted (OU)	Output polarity: Non-inverted (OU)	Output polarity: Non-inverted (OU)	Output polarity: Non-inverted (OU)	Output polarity: Non-inverted (OU)
Up signal sync.: None	Up signal sync.: None	Up signal sync.: None	Up signal sync.: None	Up signal sync.: None
Keep signal sync.: None	Keep signal sync.: None	Keep signal sync.: None	Keep signal sync.: None	Keep signal sync.: None
Mode signal sync.: Bypass	Mode signal sync.: Bypass	Mode signal sync.: Bypass	Mode signal sync.: Bypass	Mode signal sync.: Bypass
Connections	Connections	Connections	Connections	Connections
Clock: OSC1	Clock: OSC1	Clock: OSC0 /8	Clock: OSC0	Clock: OSC0 /8
Clock source: OSC1 Freq.	Clock source: OSC1 Freq.	Clock source: OSC0 Freq. /8	Clock source: OSC0 Freq.	Clock source: OSC0 Freq. /8
Clock frequency: 2.048 MHz	Clock frequency: 2.048 MHz	Clock frequency: 256 Hz	Clock frequency: 2.048 kHz	Clock frequency: 256 Hz

Figure 9: Delay Macrocells Settings

6.7 P DLY Configuration

P DLY configuration is shown in Figure 10.

P DLY	
Mode:	Both edge delay
Delay value:	500 ns

Figure 10: P DLY Settings

6.8 LUTs Configurations

LUTs configurations are shown in Figure 11.

3-bit LUT0/DFF/LATCH3	2-bit LUT0/DFF/LATCH0	2-bit LUT1/DFF/LATCH1	2-bit LUT2/DFF/LATCH2	2-bit LUT3/PGEN																																																																																																																																																																																																																																																																																																																																																																																																																																									
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Figure 11: LUTs Settings

6.9 Digital Rheostat 0 Configuration

Digital Rheostat 0 configuration is shown in Figure 12.

Analog Front End for Heart Rate Monitor

Digital Rheostat0

Mode:

Charge Pump Enable:

Charge Pump Clock:

Auto-Trim:

Active level for UP/DOWN:

Resistance (initial data):
(Range: 0 - 1023)

Connections

UP/DOWN source:

Clock:

Figure 12: Digital Rheostat 0 Settings

6.10 Analog Switch 1 Configuration

Analog Switch 1 configuration is shown in Figure 13.

SWITCH1

Mode:

Big NMOS control:

Small PMOS enable:

Half Bridge Dead Time Select:

Figure 13: Analog Switch 1 Settings

6.11 I²C Macrocell Configuration

I²C macrocell uses default configurations.

6.12 GPIOs Configurations

GPIOs configurations are shown in Figure 14.

PIN 16 (GPIO2)	PIN 17 (GPIO3)	PIN 18 (GPIO4)	PIN 12 (GPIO0)	PIN 15 (GPIO1)
I/O selection: <input type="text" value="Digital output"/>	I/O selection: <input type="text" value="Analog input/out"/>	I/O selection: <input type="text" value="Analog input/out"/>	I/O selection: <input type="text" value="Analog input/out"/>	I/O selection: <input type="text" value="Analog input/out"/>
Input mode: <input type="text" value="None"/>	Input mode: <input type="text" value="Analog input/out"/>	Input mode: <input type="text" value="Analog input/out"/>	Input mode: <input type="text" value="Analog input/out"/>	Input mode: <input type="text" value="Analog input/out"/>
Output mode: <input type="text" value="2x open drain NM"/>	Output mode: <input type="text" value="Analog input/out"/>	Output mode: <input type="text" value="Analog input/out"/>	Output mode: <input type="text" value="Analog input/out"/>	Output mode: <input type="text" value="Analog input/out"/>
Resistor: <input type="text" value="Floating"/>	Resistor: <input type="text" value="Floating"/>	Resistor: <input type="text" value="Floating"/>	Resistor: <input type="text" value="Floating"/>	Resistor: <input type="text" value="Floating"/>
Resistor value: <input type="text" value="Floating"/>	Resistor value: <input type="text" value="Floating"/>	Resistor value: <input type="text" value="Floating"/>	Resistor value: <input type="text" value="Floating"/>	Resistor value: <input type="text" value="Floating"/>

PIN 20 (GPIO6)	PIN 19 (GPIO5)	PIN 21 (GPIO)
I/O selection: <input type="text" value="Analog input/out"/>	I/O selection: <input type="text" value="Digital output"/>	I/O selection: <input type="text" value="Digital input"/>
Input mode: <input type="text" value="Analog input/out"/>	Input mode: <input type="text" value="None"/>	Input mode: <input type="text" value="Digital in with Sch"/>
Output mode: <input type="text" value="Analog input/out"/>	Output mode: <input type="text" value="1x push pull"/>	Output mode: <input type="text" value="None"/>
Resistor: <input type="text" value="Floating"/>	Resistor: <input type="text" value="Floating"/>	Resistor: <input type="text" value="Floating"/>
Resistor value: <input type="text" value="Floating"/>	Resistor value: <input type="text" value="Floating"/>	Resistor value: <input type="text" value="Floating"/>

Figure 14: GPIOs Settings

Analog Front End for Heart Rate Monitor

7 Normal Operation Mode

The analog front-end starts operating either when the voltage at power-up input (GPIO) becomes high level or when I²C master sets I²C Virtual Input0 to 1.

The Auto-Trim process begins every time after a short delay (Delay4 time = 5.4 ms) when power-up input (I²C Virt. Input0) becomes high. The maximum duration of the Auto-Trim process is $512(\text{rheostat_code})/2048(\text{kHz_clock}) = 250 \text{ ms}$.

During the calibration procedure the analog switch is turned off and the resistance of the high pass filter divider is being changed until the voltage at the inverting input of Chopper ACMP ($V_{\text{ref}} = AV_{DD}/2$) isn't equal to the voltage at the non-inverting input of Chopper ACMP (OpAmp1 output).

After the Auto-Trim process is done AFE begins to sense heart rate. LEDs are turned on 85 times per second during short intervals (100 μs). The sample and hold circuit takes samples when LEDs are turned on after a pause of 30 μs , see Figure 15. The sample and hold principle greatly minimizes the average current consumed by the LEDs.

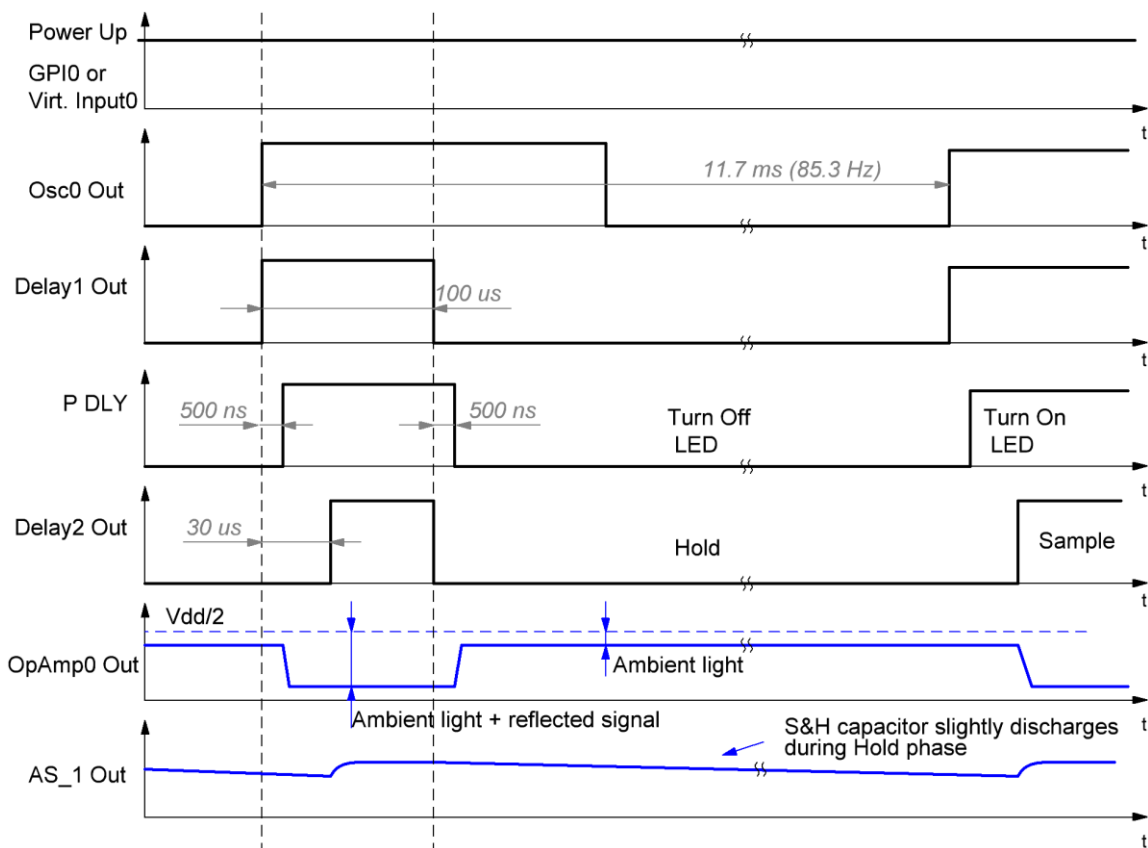


Figure 15: Sample and Hold Phases During Normal Operation Mode

8 Software Simulation and Hardware Prototype Testing

Figure 16 and Figure 17 show the simulation results of the first four seconds of AFE operation. The sensor (photodiode) is modeled as a sine voltage source with 10 mV amplitude. As shown in Figure 17, the desired point of trim ($V_{DD}/2$) is reached 114 ms after start of the Auto-Trim process. Then the Auto-Trim system continues to operate and to switch the rheostat near the desired trim point until internal Set signal is released.

Analog Front End for Heart Rate Monitor

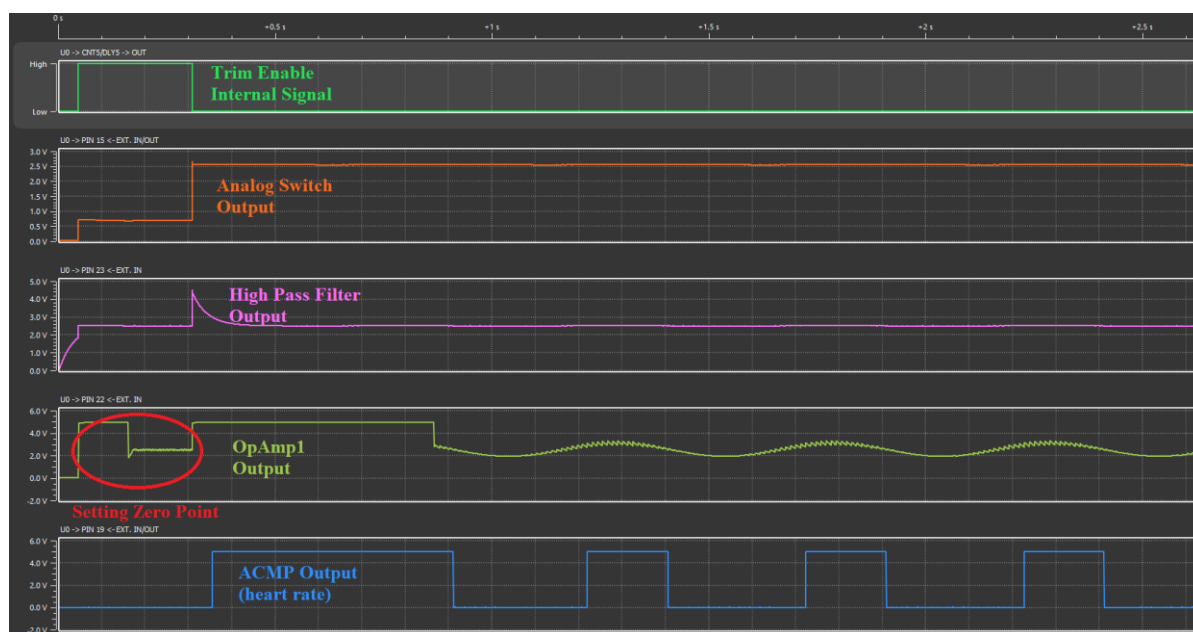


Figure 16: Simulation Results of the First Four Seconds of Operation

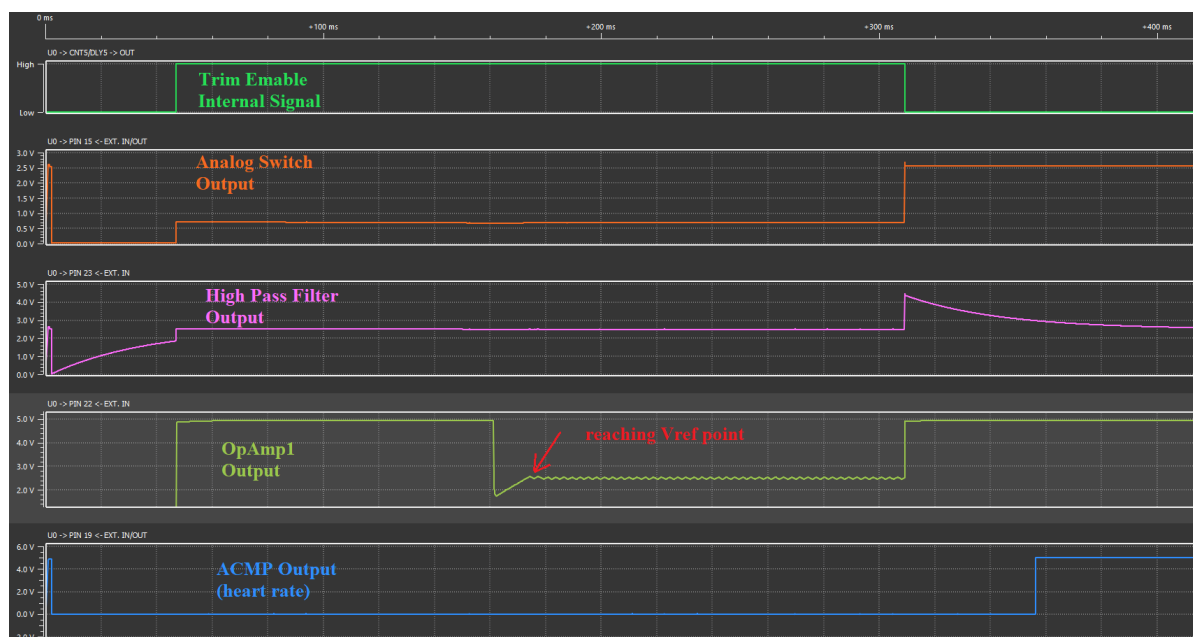


Figure 17: Simulation Results of the Auto-Trim Process

The waveforms of the hardware prototype testing are shown in [Figure 18](#).

Analog Front End for Heart Rate Monitor

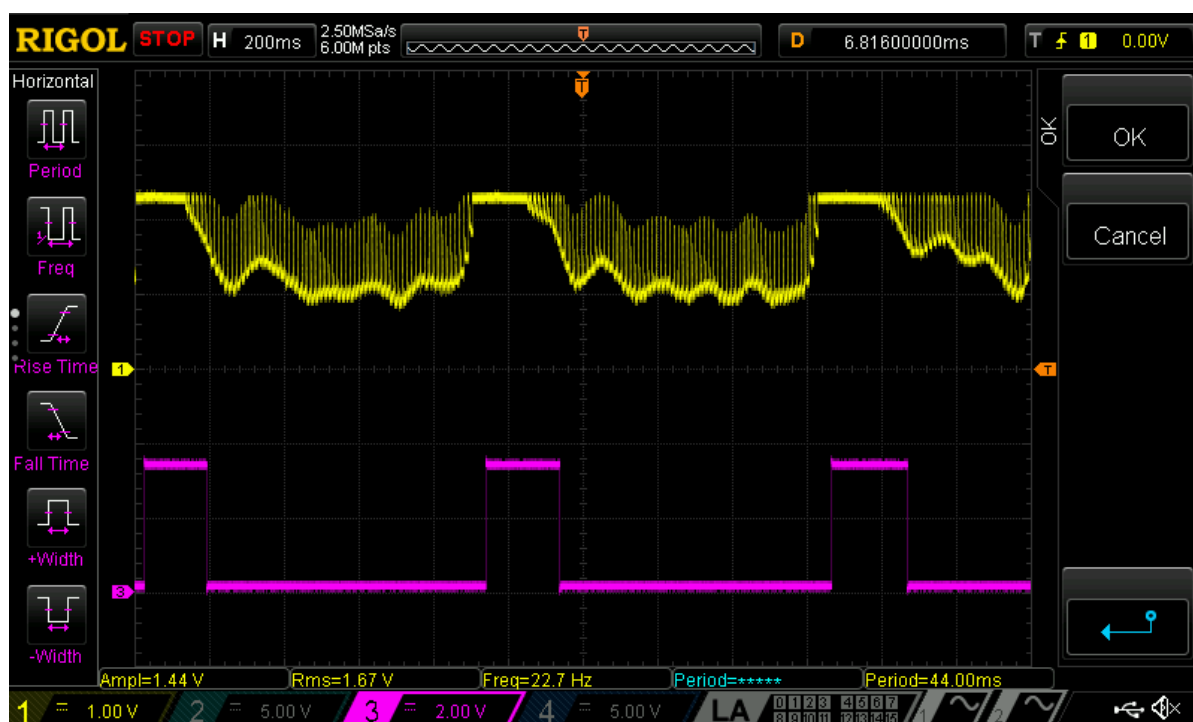


Figure 18: Analog (Yellow) and Digital (Pink) Output Signals of AFE Applied to Finger

The frequency of pulses at the digital output (Figure 18) is $f_{\text{output}} = 1.063 \text{ Hz}$. This frequency corresponds to the heart rate of $(f_{\text{output}} * 60) = 64 \text{ beats per minute}$.

The short voltage spikes on the analog output signal are caused by the LED's turn on/off. These spikes don't affect digital output signal since they are filtered by digital filter inside the SLG47004. If needed, these spikes can be also filtered by 1st order RC low pass filter placed at the OpAmp1 output.

The saturation region of the analog output signal is caused by the HD Buffer. This buffer has limited current sink capability. But this limitation of HD Buffer doesn't affect the digital output signal.

9 Conclusions

The proposed heart rate monitor is based on measuring light reflected from skin. Both signal processing and LED control are performed by a single SLG47004 IC. Additional sample and hold circuitry allows greatly reduced current consumption.

The performance of the heart rate monitor highly depends on the optical system setup: the direction of light from LEDs, the wavelength of LEDs, the distance and angle between LEDs and photodiode, and others. Also, the measurements are affected by ambient light and small movements of the sensor.

If the heart rate signal is relatively small, like a signal from the human wrist, additional software signal processing might be required.

Analog Front End for Heart Rate Monitor

Revision History

Revision	Date	Description
1.0	03-Nov-2020	Initial Version

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