Application Report

Single-Chip Pulse Oximeter Designs Based on MSP430FR2355

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ABSTRACT

This application report demonstrates the implementation of a signal chip portable pulse oximeter using MSP430FR2355 with integrated Smart Analog Combo module.

Project collateral discussed in this document can be downloaded from the following URL: https://www.ti.com/lit/zip/slaae25.

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1 Introduction

The pulse oximeter is a medical instrument for monitoring the blood oxygenation. The oxygen level and heart rate measured by the instrument can monitor the health of the user, and can also help the doctor to quickly diagnose the cause and condition of the disease. Thus, this instrument is widely used in hospitals and homes.

2 Theory of Operation

A pulse oximeter is a non-invasive device used to monitor the pulse rate and peripheral oxygen saturation (SpO2 %) of blood.

In a pulse oximeter, the calculation of the level of oxygenation of blood (SpO2) is based on measuring the intensity of light that has been attenuated by body tissue. SpO2 is defined as the ratio of the level oxygenated hemoglobin (HbO2) over the total hemoglobin level (oxygenated hemoglobin and de-oxygenated hemoglobin (Hb)):

$$SpO_2 = \frac{HbO_2}{Total\ Hemoglobin} \tag{1}$$

In principle, the HbO2 and Hb respond differently to different wavelengths of light. Hb absorbs more red light compared to infrared (IR) light, whereas, HbO2 absorbs more infrared light. As shown in Figure 2-1, when Red and IR Light Emitting Diodes (LEDs) are driven alternately through a finger, the unabsorbed light received at the other end of the finger (where a photodiode is used as the sensing element) corresponds to the concentration of Hb and HbO2 in the blood.

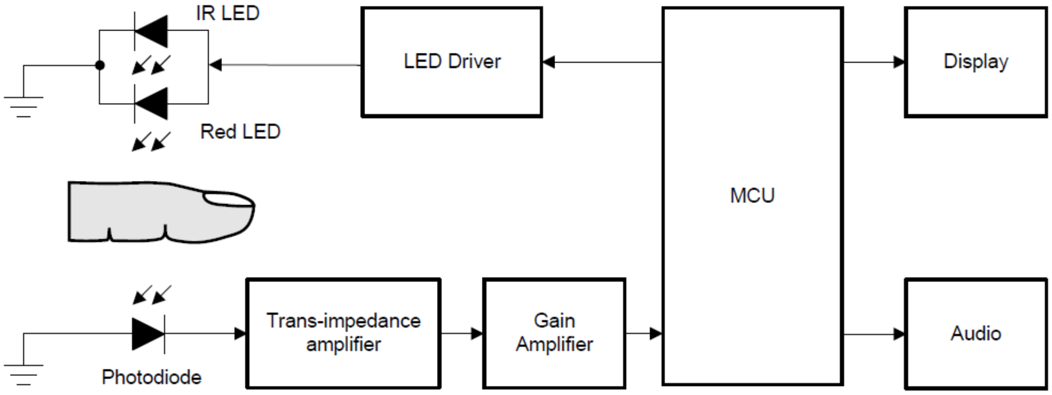


Figure 2-1. Block Diagram of Pulse Oximeter

Thus, two different wavelengths of light are used, each is turned on and measured alternately. By using two different wavelengths, the mathematical complexity of measurement can be reduced.

$$R = \frac{\log(I_{ac})\lambda_1}{\log(I_{ac})\lambda_2} \qquad SpO_2\ \alpha\ R \tag{2}$$

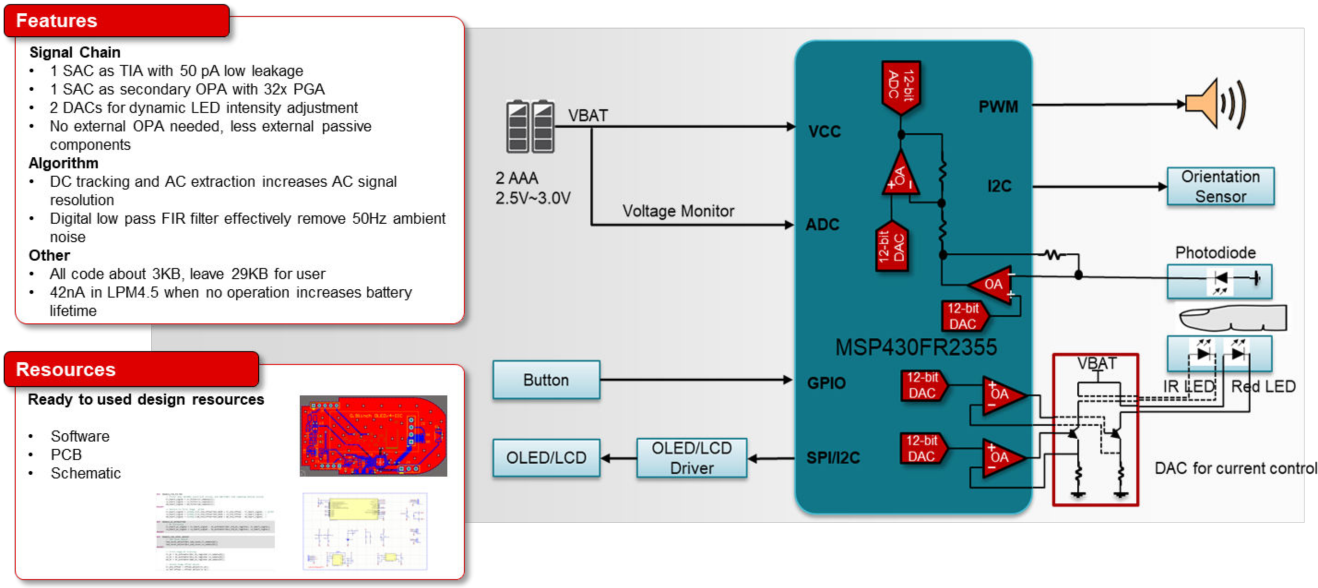
Where λ_1 and λ_2 represents the two different wavelengths of light used.

There is a DC and an AC component in the measurements. It is assumed that the DC component is a result of the absorption by the body tissue and veins. The AC component is the result of the absorption by the arteries.

In practice, the relationship between SpO2 and R is not as linear as indicated by the above formula. For this reason, a look up table is used to provide a correct reading.

3 Single-Chip Design

Figure 3-1 shows the proposed block diagram of a single-chip pulse oximeter design using the MSP430FR235x. All four SACs are utilized optimally: two for the LED drive stage (Red and IR) and two for the photodiode signal conditioning (TIA and gain stage). Internal clocks and voltage references are selected to minimize the use of external components thus reducing the overall Bill of Material (BOM) cost as well as the footprint of the design.



Features

Signal Chain
- 1 SAC as TIA with 50 pA low leakage
- 1 SAC as secondary OPA with 32x PGA
- 2 DACs for dynamic LED intensity adjustment
- No external OPA needed, less external passive components

Algorithm
- DC tracking and AC extraction increases AC signal resolution
- Digital low pass FIR filter effectively remove 50Hz ambient noise

Other
- All code about 3KB, leave 29KB for user
- 42nA in LPM4.5 when no operation increases battery lifetime

Resources

Ready to used design resources

- Software
- PCB
- Schematic

Figure 3-1. Single-Chip Solution for Pulse Oximeter

4 Hardware

As shown in Figure 4-1, it shows the connection structure of the SAC inside FR235x.

- SAC0 as a TIA
- SAC2 as the gain stage
- ADC will capture SAC0 and SAC2 output
- SAC1 and SAC3 use to drive IR and RED LED.

From the structure in Figure 4-1, you can get the voltage of SAC0 output (Vo1):

$$V_{o1} = I * R_f + V_{DAC1} \tag{3}$$

The voltage of SAC2 output (Vo2):

$$V_{o2} = \left(\frac{R_2}{R_1} + 1\right) V_{DAC2} - \frac{R_2}{R_1} V_{o1} \tag{4}$$

In order to improve the SNR of the analog-to-digital converter (ADC) signal, the output signal of SAC2 needs to be adjusted at ADC VREF/2. Therefore, the value of DAC2 needs to be adjusted in real time according to the output of SAC0.

$$\begin{aligned} V_{o2} &= (g+1)V_{DAC2} - gV_{o1} \qquad g = \frac{R_2}{R_1} \\ &= \boxed{(g+1)V_{DAC2} - gV_{o1\_dc}} - gV_{o1\_ac} \\ &\qquad\downarrow \\ &\frac{VREF}{2} = 2048 \end{aligned} \tag{5}$$

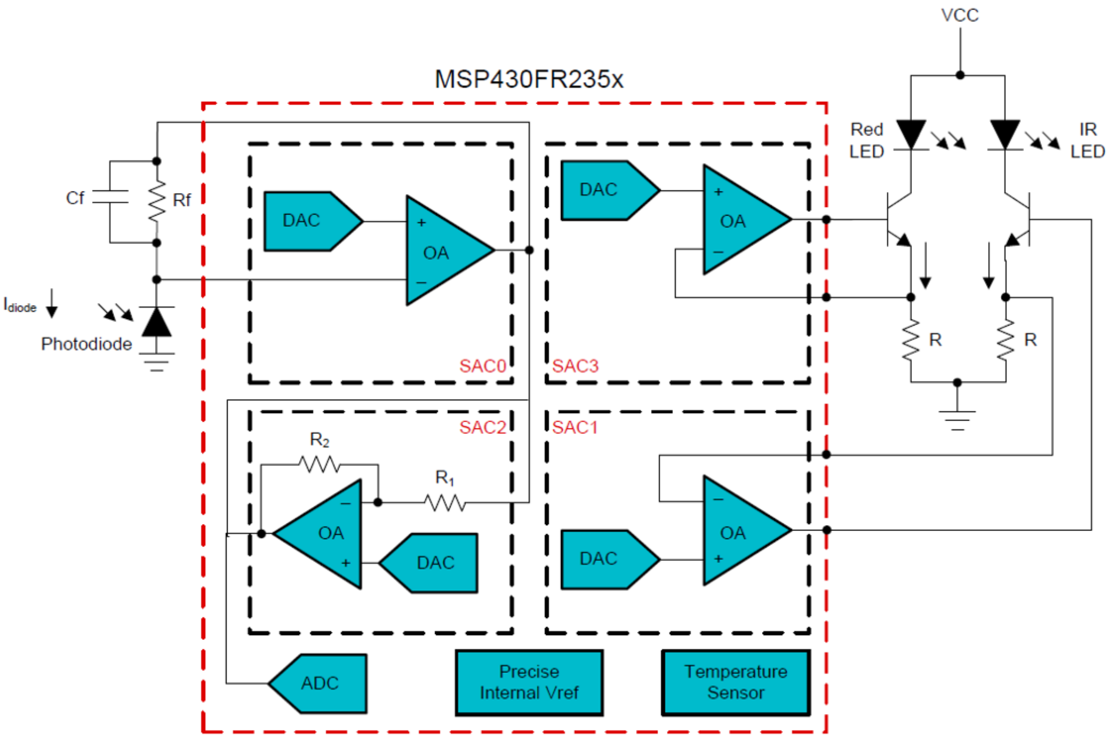


Figure 4-1. Block Diagram of 4*SAC for Pulse Oximeter

In the schematic (Figure 4-2), you can find that:

- Two SACs are used with transistors to drive RED*IR LEDs
- SAC0+SAC2 are connected internally to amplify photodiode signal
- A button is used to wake up the system and start to measure
- A SPI interface is used to drive the organic light-emitting diode (OLED) screen (include driver)
- An SBW and BSL inter-integrated circuit (I2C) mode program debugging port
- An universal asynchronous receiver/transmitter (UART) serial port used to communicate with GUI

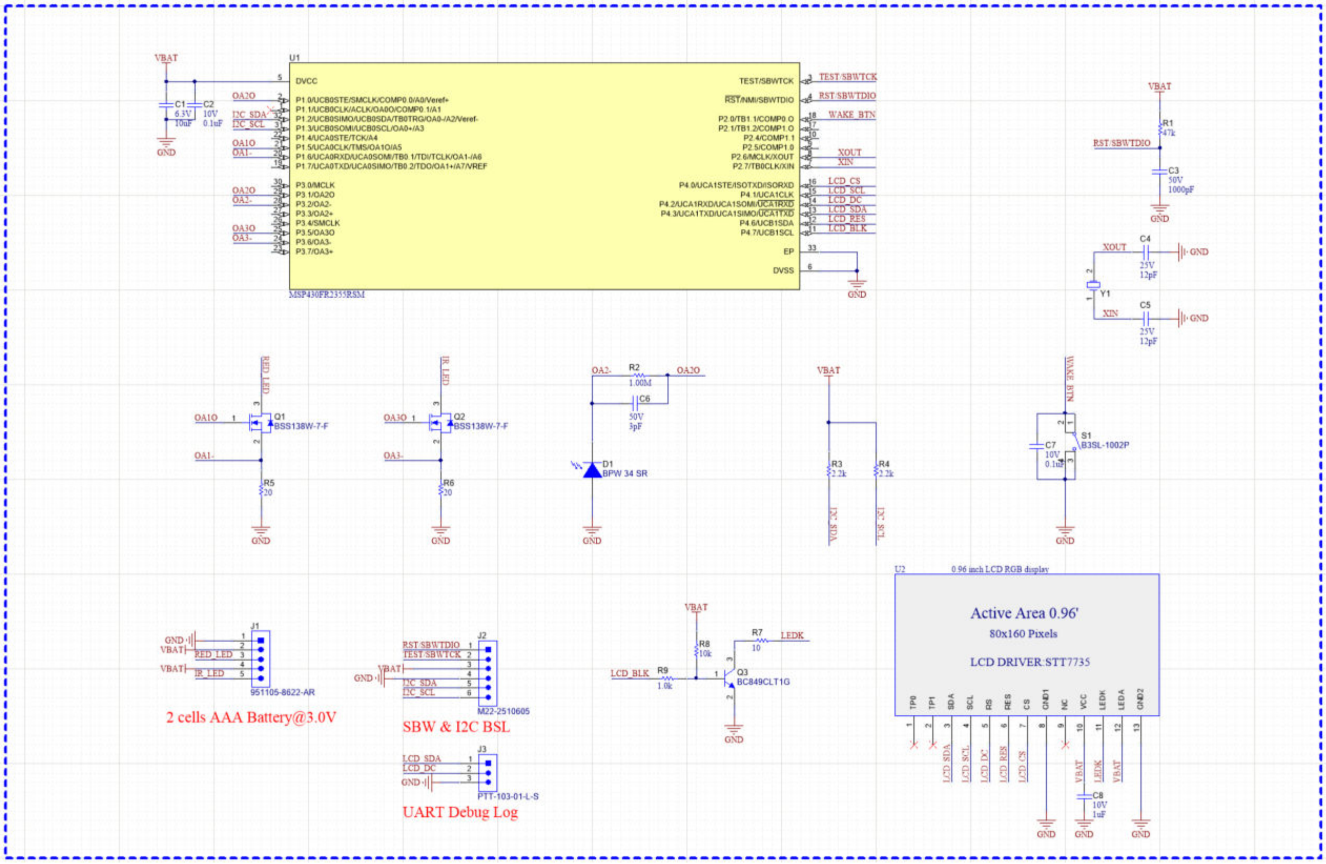


Figure 4-2. Schematic of FR2355 for Pulse Oximeter

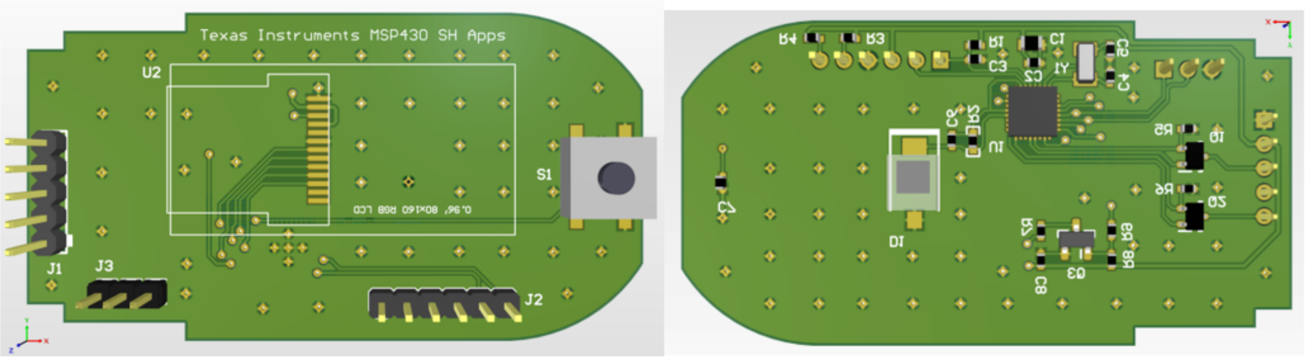


Figure 4-3. Layout of FR2355 for Pulse Oximeter

5 Software

5.1 Sample and Condition the PIN Diode Signal

The photo-diode generates a current from the received light. This current signal is amplified by a transimpedance amplifier SAC0, one of the four built in SAC, is used to amplify this signal. Since the current signal is very small, it is important for this amplifier to have a low drift current. The large DC component is caused by the lesser oxygen bearing parts of the body tissue and scattered light. This part of the signal is proportional to the intensity of the light emitted by the LED.

The small AC component is made up of the light modulation by the oxygen bearing parts such as the arteries plus noise from ambient light at 50/60 Hz. It is this signal that needs to be extracted and amplified. The LED level control tries to keep the output of SAC0 within a preset range via control SAC1 and SAC3. The Normal Red and IR LEDs are controlled separately to within this preset range. Effectively, the output from both LEDs matches with each other within a small tolerance.

The extraction and amplification of the AC component of the SAC0 output is performed by the second stage SAC2. The DC tracking filter extracts the DC component of the signal and is used as an offset input to SAC2. As SAC2 would only amplify the difference it sees between the two terminals, only the AC portion of the incoming signal is amplified. The DC portion is effectively filtered out.

The offset of SAC2 is also amplified and added to the output signal. This needs to be filtered off later on.

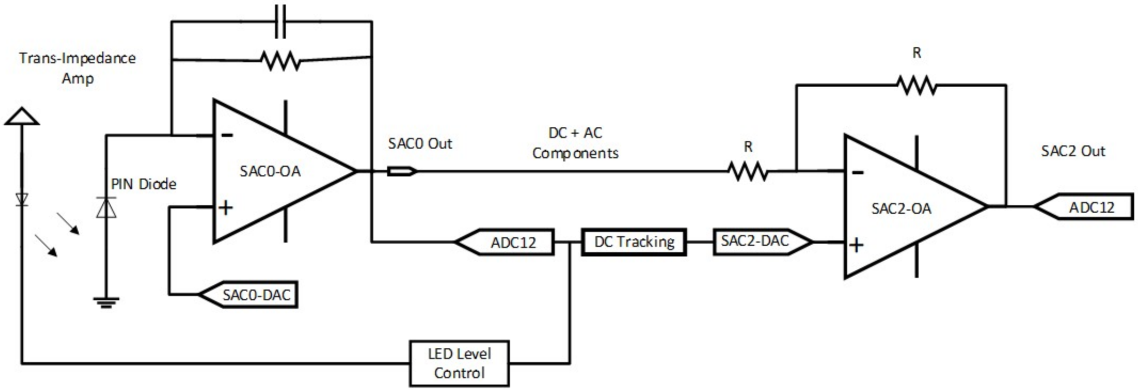


Figure 5-1. Input Front End Circuit and LED Control

5.2 Sample and Measurement Sequence

A Timer is used to control the multiplex sequence and automatically start the ADC conversion.

In this timer periods, set three CCRx values for comparison, switch the LED in each comparison interrupt and run ADC acquisition.

- Timer Start:
  - Trigger SAC1 to lightt up the IR LED
- CCR1 Interrupt:
  - Enable ADC to capture IR LED TIA and PGA signal
  - Close SAC1
  - Trigger SAC3 to lightt up the RED LED
- CCR2 Interrupt:
  - enable ADC to capture RED LED TIA and PGA signal
  - Close SAC3
- CCR3 Interrupt:
  - enable ADC to capture ambient light TIA and PGA signal

The ADC conversion is triggered automatically. It takes two samples: one of the SAC0 output for DC tracking and one of the SAC2 output, to calculate the heart beat and oxygen level.

To conserve power, at the completion of the ADC conversion an interrupt is generated to tell the MCU to switch off the LED.

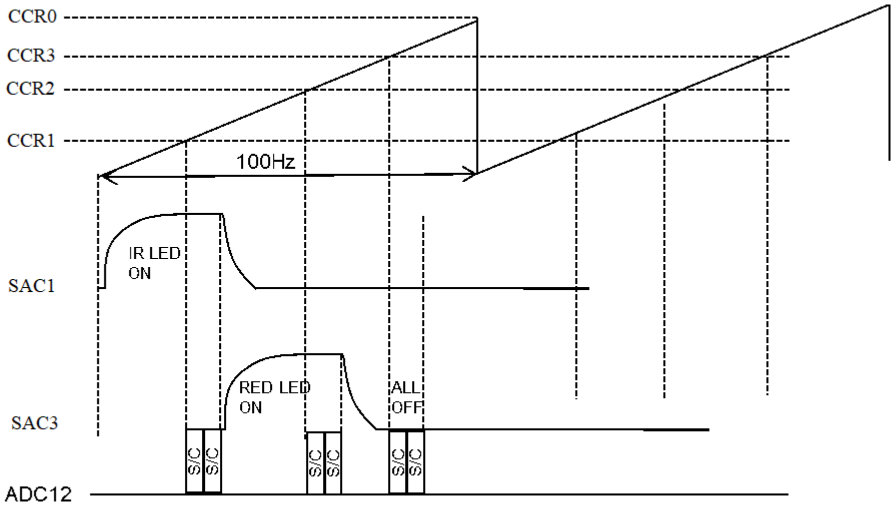


Figure 5-2. Sample and Measurement Sequence

5.3 First Stage DC Tracking

A simple a low-pass IIR digital filter is used to track the DC value of the signal after the TIA, and adjust the offset of the second-stage amplification.

$$y_n = y_{n-1} + (x_n - y_{n-1})/2^k \quad (6)$$

A DC tracking filter is illustrated in Figure 5-3.

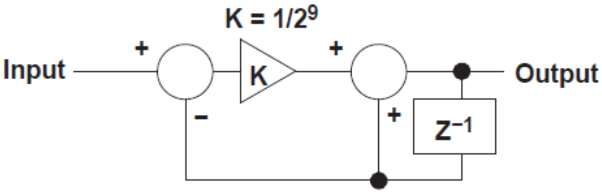


Figure 5-3. Tacking Filter Block Diagram

This is an IIR filter. The working of this filter is best understood intuitively. The filter adds a small portion of the difference between its input and its last output value to its last output value to form the new output value. It there is a step change in the input, the output changes itself to be the same as the input over a period of time. The rate of change is controlled by the coefficient K. K is worked out by experiment. So, if the input contains an AC and DC component, the coefficient K is made sufficiently small to generate a time constant relative to the frequency of the AC component so that over a length of time the AC will cancel itself out in the accumulation process and the output would only track the DC component of the input.

As shown in Figure 5-4, high frequency noise is filtered out by IIR, and it can track the DC value of ADC data well.

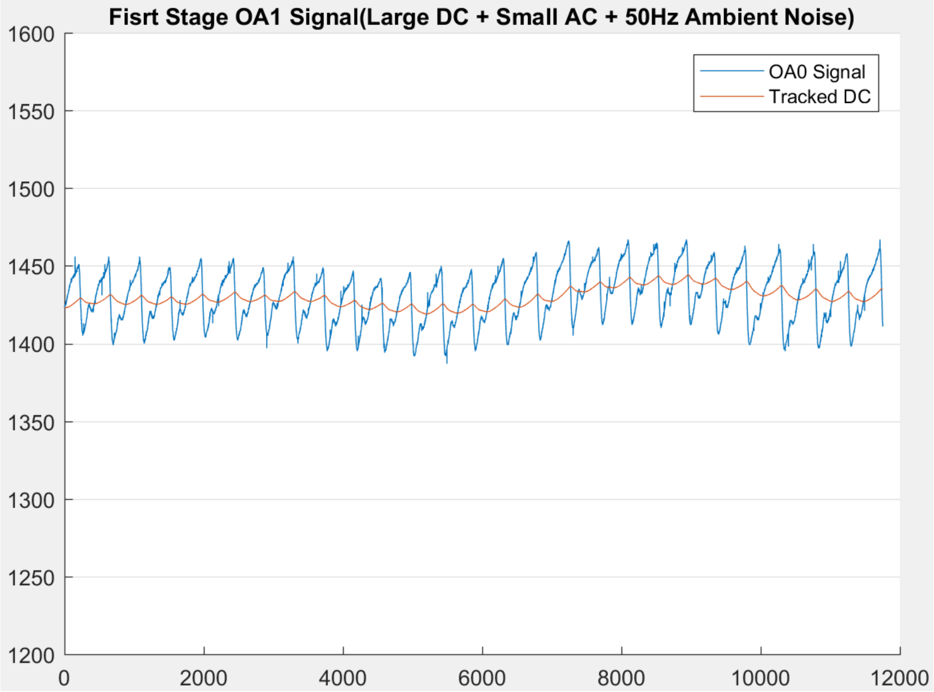


Figure 5-4. IIR DC Tracking Filter

5.4 Low-Pass FIR Filter

In order to increase the SNR of the ADC signal, the FIR filtering is used to filter out the 50Hz ambient noise in this solution. As shown in Figure 5-5, the data after FIR filtering is smoother. And FR2355 integrates a hardware multiplier (MPY32) module, which can speed up FIR filtering.

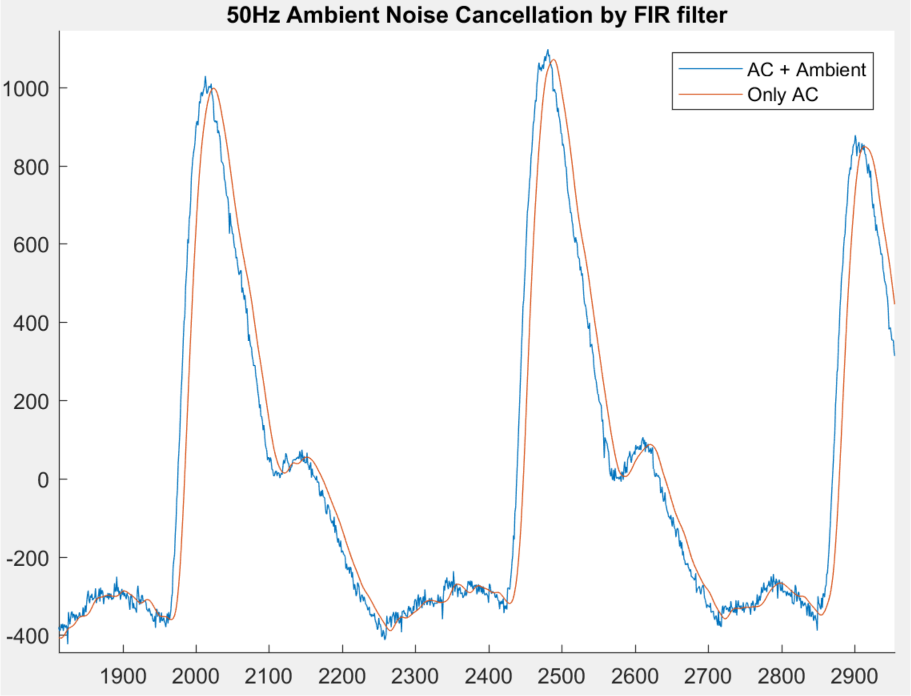


Figure 5-5. Low-Pass FIR Filter

5.5 Calculate Heart and SpO2

As shown in Figure 5-6, this is the ADC value of photodiode signal after filtered and amplify. You can define the highest point in a period as onset and the lowest point as peak.

You need to calculate AC and DC values for the RED/IR signal, and then use the below formula to calculate the blood oxygen level.

- For AC value, find the onset and peak point.
- For the value of A, B, C in this formula, it is a medical calibration constant that requires a lot of test data to calculate.

For the heart rate, it can be calculated by the time of two onset/peak points.

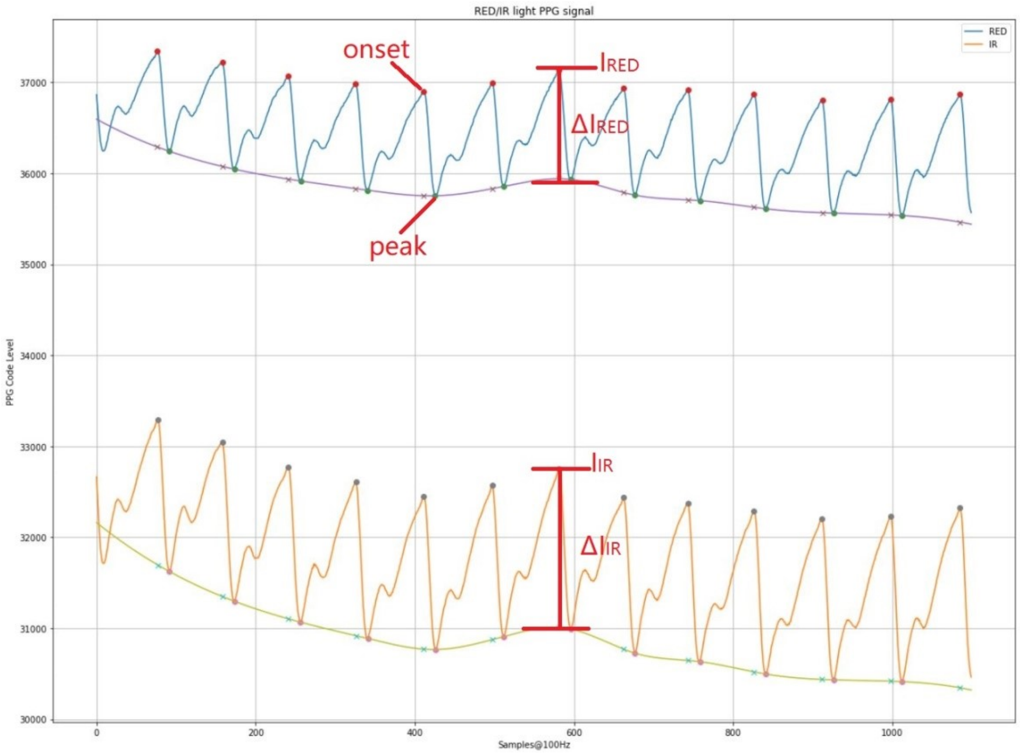


Figure 5-6. ADC Value for IR & RED LED Drive

6 Debug GUI

There is a GUI for this solution that can help you quickly evaluate and adjust parameters. The GUI communicate with MCU through UART, MCU can send the collected real-time ADC data to PC. And You can check if the parameter in the code are reasonable by observing the current ADC value.

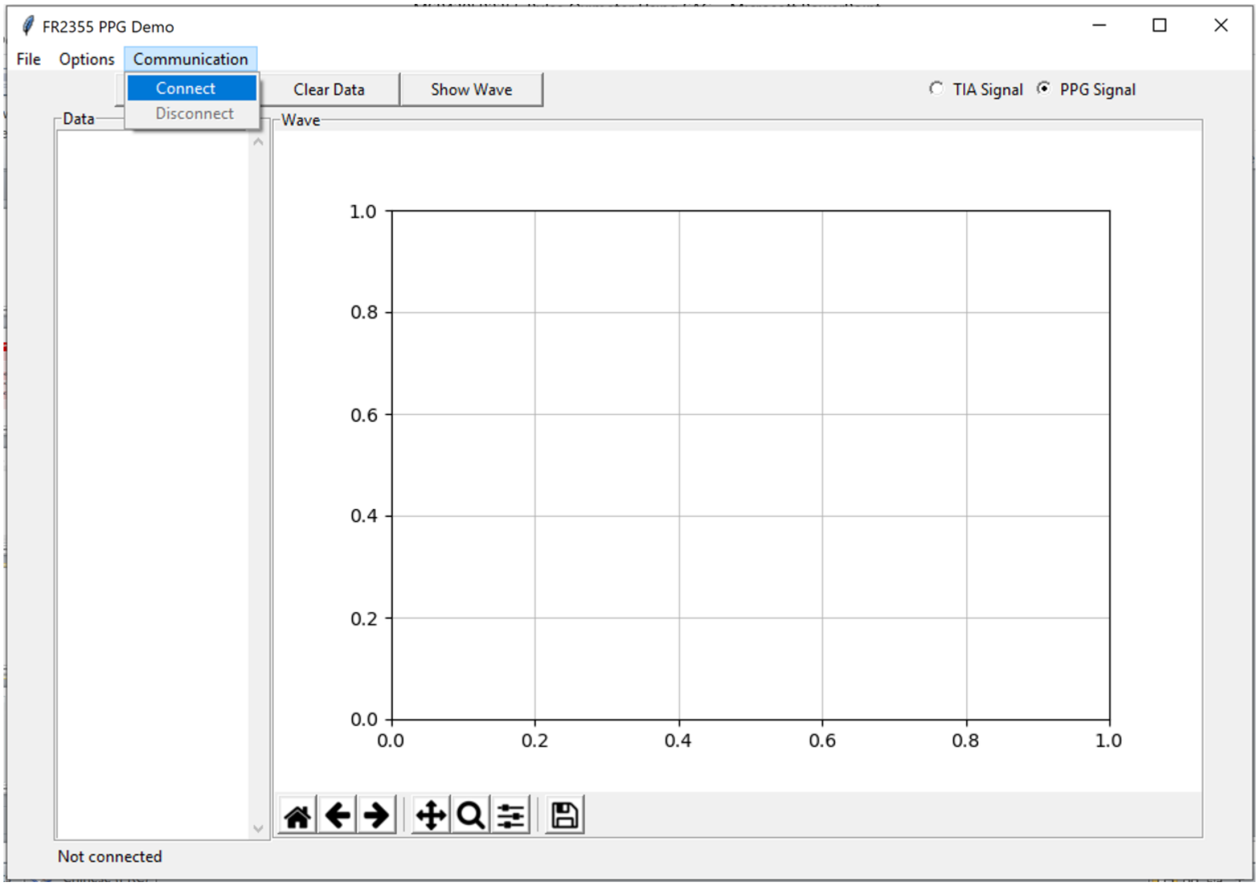
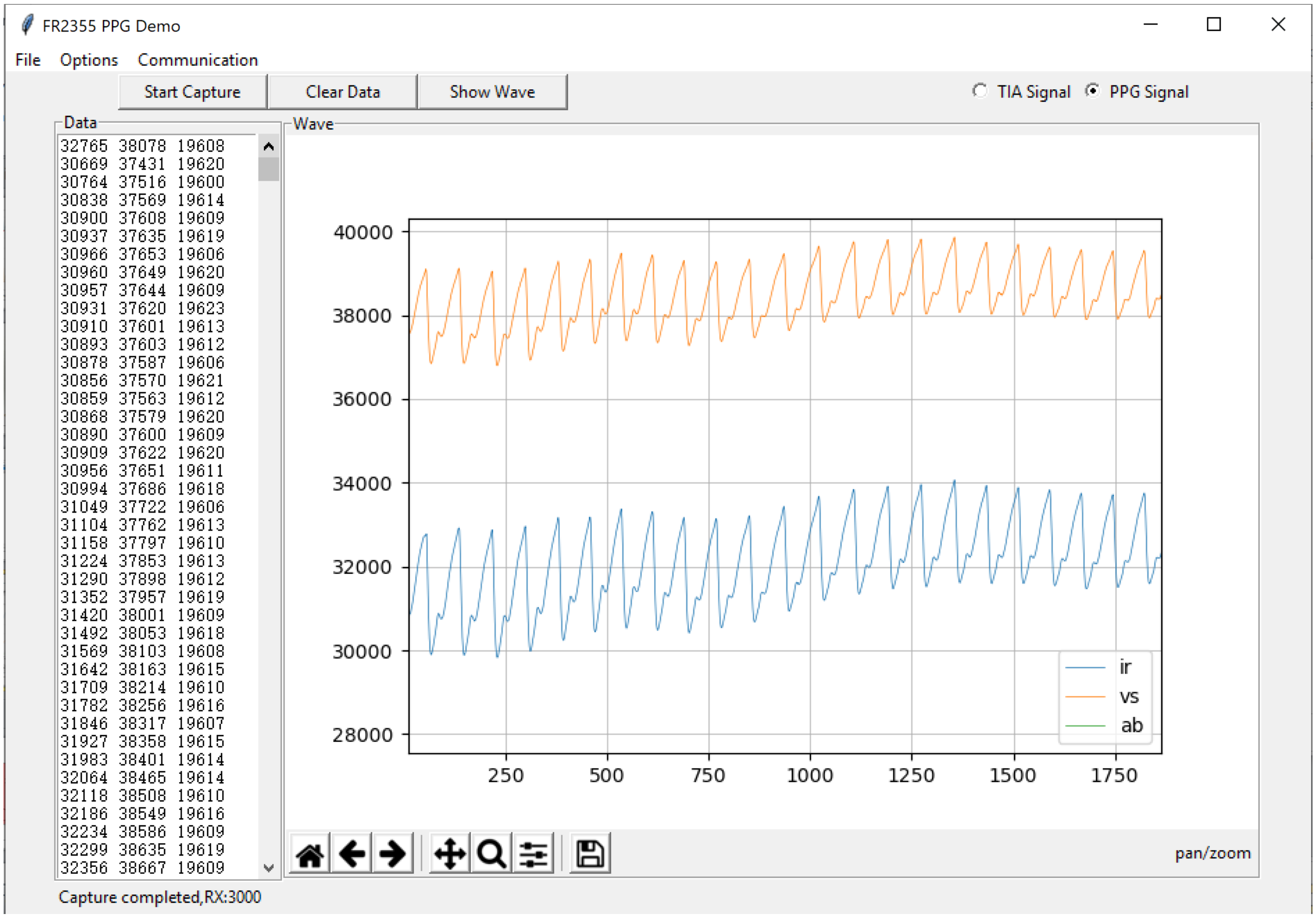


Figure 6-1. GUI for Pulse Oximeter

Connect the Demo board and GUI through the following steps:

1. Connect demo to Launchpad, and Launchpad to PC.
2. Change the “ENABLE_DATA_LOG” to 1, and re-compile/program code.
3. Open PPG_GUI.exe as Figure 6-1.
4. Click Communication- > Connect.
5. Choose the TIA Signal or the PPG Signal, click capture.
6. After finishing the capture, data wave can be shown in left frame by clicking ‘Show Wave’ .

Figure 6-2 shows the data sent by the MCU to the GUI.



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32765 38078 19608
30669 37431 19620
30764 37516 19600
30838 37569 19614
30900 37608 19609
30937 37635 19619
30966 37653 19606
30960 37649 19620
30957 37644 19609
30931 37620 19623
30910 37601 19613
30893 37603 19612
30878 37587 19606
30856 37570 19621
30859 37563 19612
30868 37579 19620
30890 37600 19609
30909 37622 19620
30956 37651 19611
30994 37686 19618
31049 37722 19606
31104 37762 19613
31158 37797 19610
31224 37853 19613
31290 37898 19612
31352 37957 19619
31420 38001 19609
31492 38053 19618
31569 38103 19608
31642 38163 19615
31709 38214 19610
31782 38256 19616
31846 38317 19607
31927 38358 19615
31983 38401 19614
32064 38465 19614
32118 38508 19610
32186 38549 19616
32234 38586 19609
32299 38635 19619
32356 38667 19609
```

Capture completed,RX:3000

Figure 6-2. Data in GUI for Pulse Oximeter

7 Test Result

Tests were done on the blood oxygen simulator base on this demo. The test results are shown in Figure 7-1. You can find that our solution can measure the blood oxygen and heart rate values accurately.

Figure 7-1. Test Base on Blood Oxygen Simulator

A comparison was done with the mass-produced pulse oximeter on the market. The results are shown in Figure 7-2. In the same time, the standard pulse oximeter and the demo were used to measure two fingers. The measurement results showed that the data was consistent.

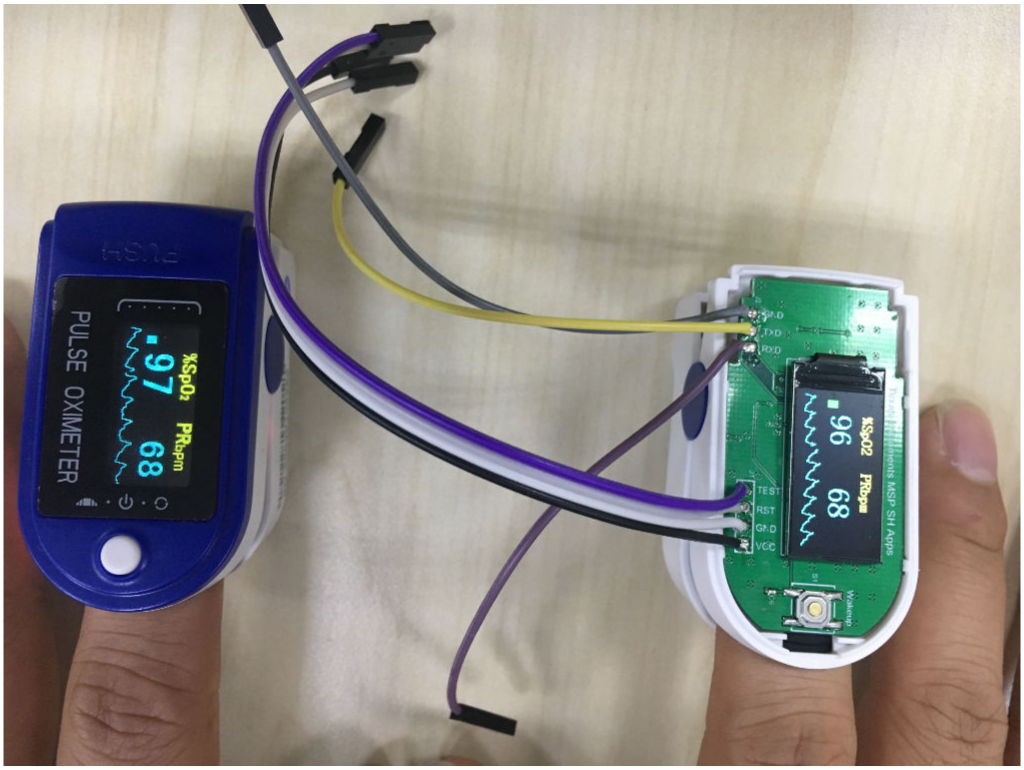

Figure 7-2. Comparison Test (Left: MP Pulse Oximeter, Right: Demo Base on FR2355)

8 Summary

The MSP430FR235x comes in a small 6 x 6 mm VQFN40 and 4 x 4 mm VQFN32 package. It integrates four SACs (configurable signal chain), temperature sensor, precise voltage reference, and internal clock oscillators. Overall, it eliminates the use of multiple external components. Thus, MSP430FR235x device not only enables true single chip pulse oximeter design, but also helps in reducing the form factor of the overall solution due to integrated analog signal chain elements.

9 References

- Texas Instruments: *MSP430FR235x, MSP430FR215x Mixed-Signal Microcontrollers Data Sheet*
- Texas Instruments: *MSP430FR4xx and MSP430FR2xx Family User's Guide*
- Texas Instruments: *How to Use the Smart Analog Combo in MSP430™ MCUs*
- Texas Instruments: A Single-Chip Pulsoximeter Design Using the MSP430.
- Texas Instruments: *MSP430's Analog Combo Enables True Single-Chip Pulse Oximeter Designs*
- Texas Instruments: *Revised Pulsoximeter Design Using the MSP430*
- Digital Signal Processing (DSP) Library for MSP430 Microcontrollers.

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