Design Guide: TIDA-010267

Single-Chip Pulse Oximeter Reference Design With 90-dB Dynamic Range for Lower PI

Description

This reference design demonstrates the analog capabilities of the MSPM0L1306 in a low-cost, single-chip pulse oximeter design. The operational amplifiers (OPAs) within the MSPM0L1306 serve as the trans-impedance amplifier (TIA) and current control driver with zero-drift, low-noise capabilities. The integrated high-speed, analog-to-digital converter (ADC) provides the ability to oversample and achieve high levels of dynamic range. This design features a GUI to visualize photoplethysmography (PPG) waveforms and vitals measurements of heart rate in beats per minute (BPM) and peripheral oxygen saturation (%SpO_2).

Resources

TIDA-010267	Design Folder
MSPM0L1306	Product Folder
MSPM0-SDK	Design and Development
GUI	GUI Gallery

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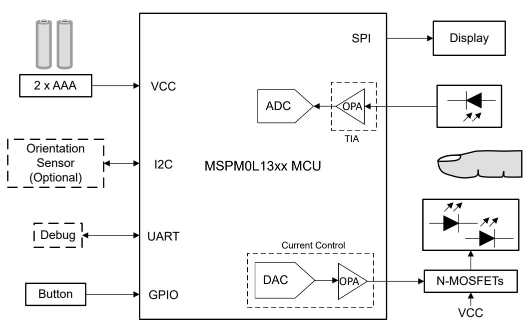
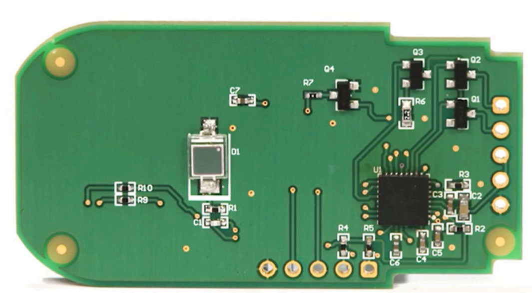
Features

- Achievable heart rate range of 30 – 240 beats per minute (BPM) and perfusion index (PI) range of 0.1% – 20% for a wide variety of pulse strengths and greater reliability
- 90-dB dynamic range achievable from internal 12-bit ADC through oversampling
- Standard display resolution of 1 BPM and 1% SpO_2 for accurate vitals readings
- Longer battery life with ultra-low (< 83 nA) shutdown current during device off-time

Applications

- Clinical pulse oximeter
- Multiparameter patient monitoring





1 System Description

The pulse oximeter is a medical instrument for monitoring the saturation of oxygen in the blood and the pulse rate. 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.

A pulse oximeter is a non-invasive device used to monitor the pulse rate and peripheral oxygen saturation (% SpO_2) of blood.

In a pulse oximeter, the calculation of the level of oxygenation of blood (SpO_2) is based on measuring the intensity of light that has been attenuated by body tissue. SpO_2 is defined as the ratio of the level oxygenated hemoglobin (HbO_2) over the total hemoglobin level (oxygenated hemoglobin and de-oxygenated hemoglobin (Hb)), see Equation 1.

$$\mathrm{SpO_2} = \frac{\mathrm{HbO_2}}{\mathrm{HbO_2} + \mathrm{Hb}} \tag{1}$$

In principle, the HbO_2 and Hb respond differently to different wavelengths of light. Hb absorbs more red light compared to infrared (IR) light, whereas, HbO_2 absorbs more infrared light. As shown in Figure 1-1, when Red and IR Light Emitting Diodes (LEDs) are driven alternately through a finger, the amount of unabsorbed light that travels through the finger (where a photodiode is used as the sensing element) is related to the concentration of Hb and HbO_2 in the blood.

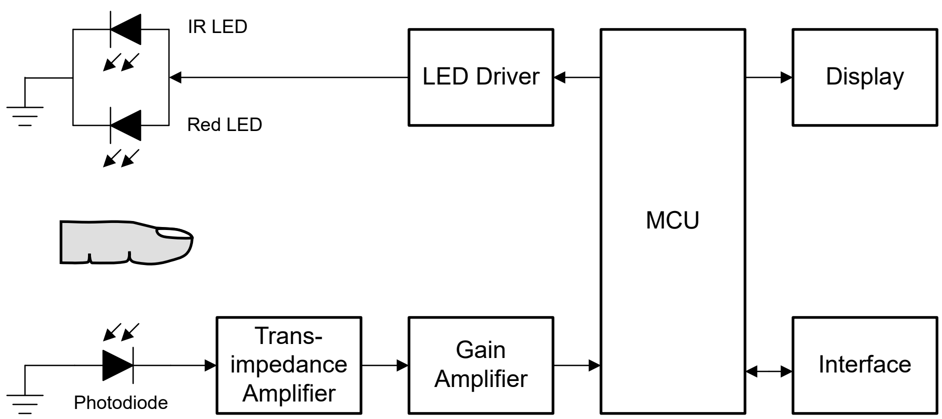


Figure 1-1. Block Diagram of Pulse Oximeter

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.

$$\mathrm{R} = \frac{\log(\mathrm{I}_{\alpha c})\lambda_1}{\log(\mathrm{I}_{\alpha c})\lambda_2} \quad \mathrm{SpO_2}\ \alpha\ \mathrm{R} \tag{2}$$

where

- λ_1 and λ_2 represent the two different wavelengths of light used

There is a DC and an AC component to the measurements. It is assumed that the DC component is a result of the absorption and scattering by body tissue, blood in the veins and capillaries, and non-pulsatile (without periodic variations) blood in the arteries. The AC component is the result of the absorption by pulsatile (with periodic variations) blood in the arteries.

In practice, the relationship between SpO_2 and R is not as linear as indicated by Equation 2. For this reason, a look up table is used to provide a correct reading.

The reliability of the R, and therefore the SpO_2, is dependent on the ability to achieve good dynamic range on the signal input. Dynamic range (DR) is calculated from the effective number of bits (ENOB) using Equation 3.

$$DR = 20 \times \log_{10}\left(2^{ENOB}\right) \quad (3)$$

2 System Overview

2.1 Block Diagram

The MSPM0 Pulse Oximeter Design uses various analog and digital peripherals to integrate a high-performance, low-cost pulse oximeter design into a single chip, as shown in Figure 2-1.

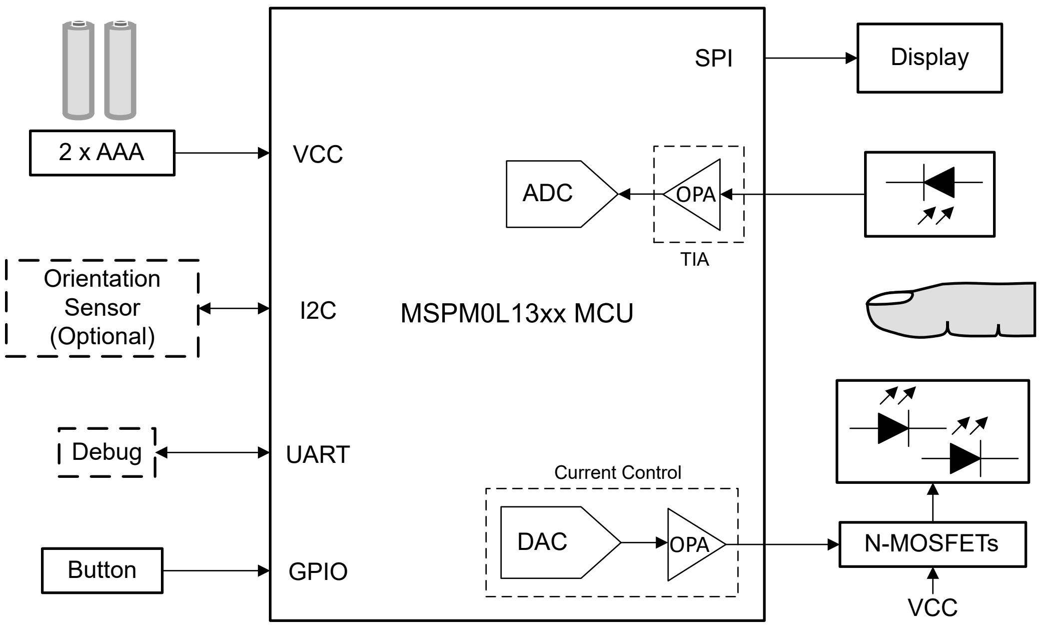


Figure 2-1. TIDA-010267 Pulse Oximeter Block Diagram

2.2 Design Considerations

Figure 2-2 illustrates the analog blocks in use on the MSPM0L1306 and how the blocks interact with the LED and photodiode parts.

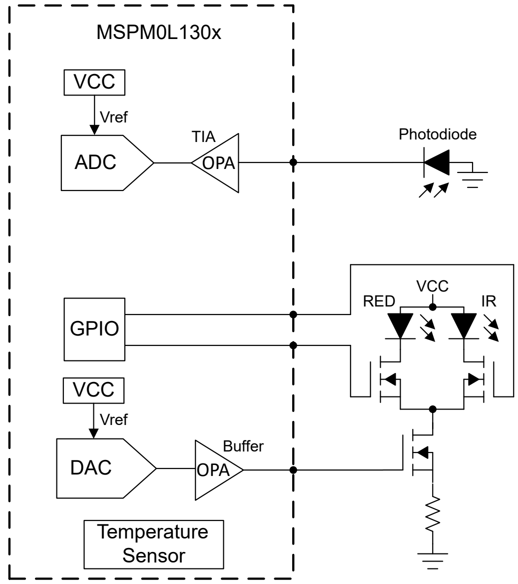


Figure 2-2. TIDA-010267 Pulse Oximeter Analog-Front End

2.2.1 Photodiode, TIA, and ADC

In TIDA-010267, the photodiodes signal, in the form of a current on the order of nano-Amps is converted to a voltage and amplified to fit in the range of the ADC of the MSPM0L1306. This is achievable using the low input bias current of the integrated OPA, allowing the design to utilize the OPA as a TIA, as shown in Figure 2-5. Using the MSPM0L1306 voltage input as a reference for the high-speed ADC, the convertor can more rapidly sample, which allows for oversampling and reduced LED on-time. An internal voltage monitoring feature in between samples, allows the MSPM0L1306 to quantify the level of the incoming signal and adjust parameters accordingly. Further features, such as internal temperature sensing, are also possible.

2.2.2 LED Driving

The AFE Block Diagram (Figure 2-2), shows that the power of each LED is managed by the MOSFET and controlled via the GPIO pins of the MSPM0L1306. These two MOSFETS control the on and off states of the LEDs respectively. TIDA-010267 uses single-part LEDs with wavelengths of 660 nm (red) and 940 nm (IR). LED brightness control is achievable thanks to the internal 8-bit DAC of the MSPM0L1306 and OPA voltage follower outputting to a common MOSFET that determines the current flow through the LEDs. Because the voltage of the battery can be monitored periodically with an internal ADC connection and internal voltage reference, it is possible to reliably attenuate the voltage output of the DAC to a known level and pinpoint the desired current flow through the LEDs.

2.2.3 Power

The TIDA-010267 is powered by 2 × AAA batteries connected directly to the MSPM0L1306. The wide supply voltage range of the MSPM0L1306, down to 1.62 V, allows for the device to be used over a larger battery life span, as AAA batteries tend to decline in voltage with use. The integrated LED driving setup on the MSPM0L1306 also powers the LEDs from the battery for a design that allows for battery-powered LED brightness control via current control from the MCU. This flexibility in power and controllable features permit the device to function well without the need for an external power IC, lowering the cost and chip count.

2.2.4 Display, Orientation, and Communication Features

Figure 2-3 and Figure 2-4 illustrate the optional feature wiring and layout space for the pulse oximeter. A display with integrated driver can be connected to SPI Port 0 of the MSPM0L1306 via 4-wire SPI for simple integration. Additionally, I2C Port 0 of the MSPM0L1306 can be used to integrate an orientation sensor to orient the display in a convenient manner for the device user. Furthermore, universal asynchronous receiver transmitter (UART) Port 1 on the MSPM0L1306 can be used for communication to receive and interpret serial data transmitted to TI's POX GUI or other serial data compatible software. Lastly, the TIDA-010267 allows for MCU programming via 10-pin SWD configuration for simplified debugging and testing with TI resources.

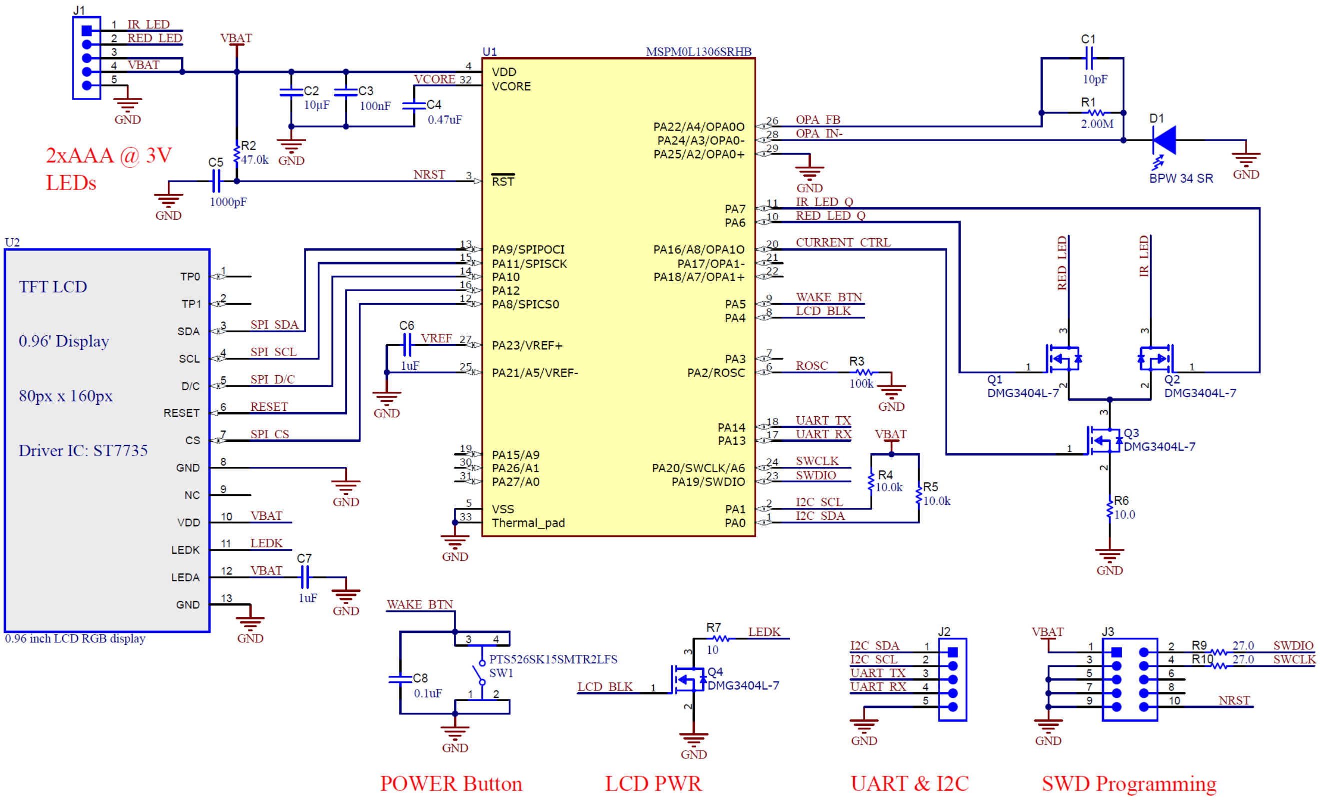


Figure 2-3. TIDA-010267 for Pulse Oximeter Schematic

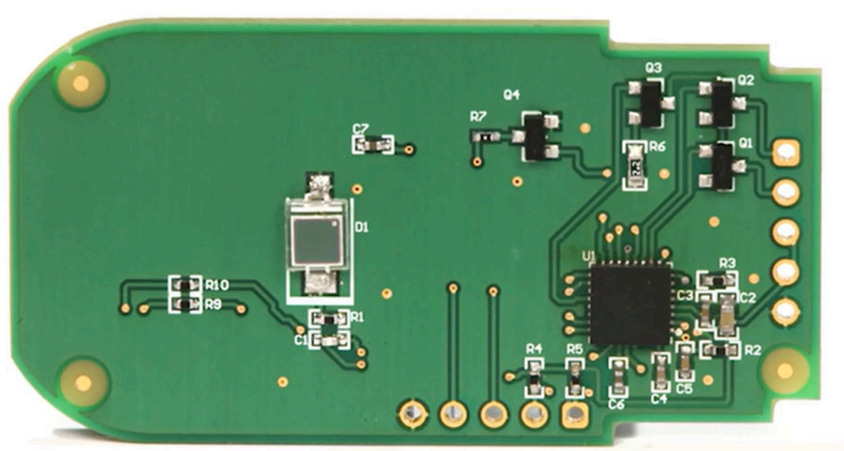


Figure 2-4. PCB of TIDA-010267 for Pulse Oximeter

2.2.5 Software

2.2.5.1 Timing Structure

Figure 2-5 illustrates the coded timing structure for pulse oximeter operation.

- To capture the natural frequencies of a PPG signal, which can vary but are generally single-digit frequencies, photodiode samples for both red and IR light are captured at 125 Hz.
- During the 8-ms period between captures, which is managed by the TIMG0 block (named T8) of the MSPM0L1306, Figure 2-5 details the operational status of several components involved in obtaining the photodiode sample.
- TIMG1 block (named T1) runs twice at the start of the 8-ms period, each time for 1 ms, to denote the on time of each red and IR LEDs, respectively.
- T1 and T8 utilize interrupts to manage activation and DAC output level timing as well as the start time for 256 ADC sample captures per LED.
- Once the captured ADC data from both LEDs is stored and the second interrupt from T1 arrives, the MSPM0L1306 deactivates both LEDs to conserve power and begin data processing and calculations.
- During this time, the ADC can switch to monitoring the internal voltage or transmitting serial data (or both) before the cycle repeats.

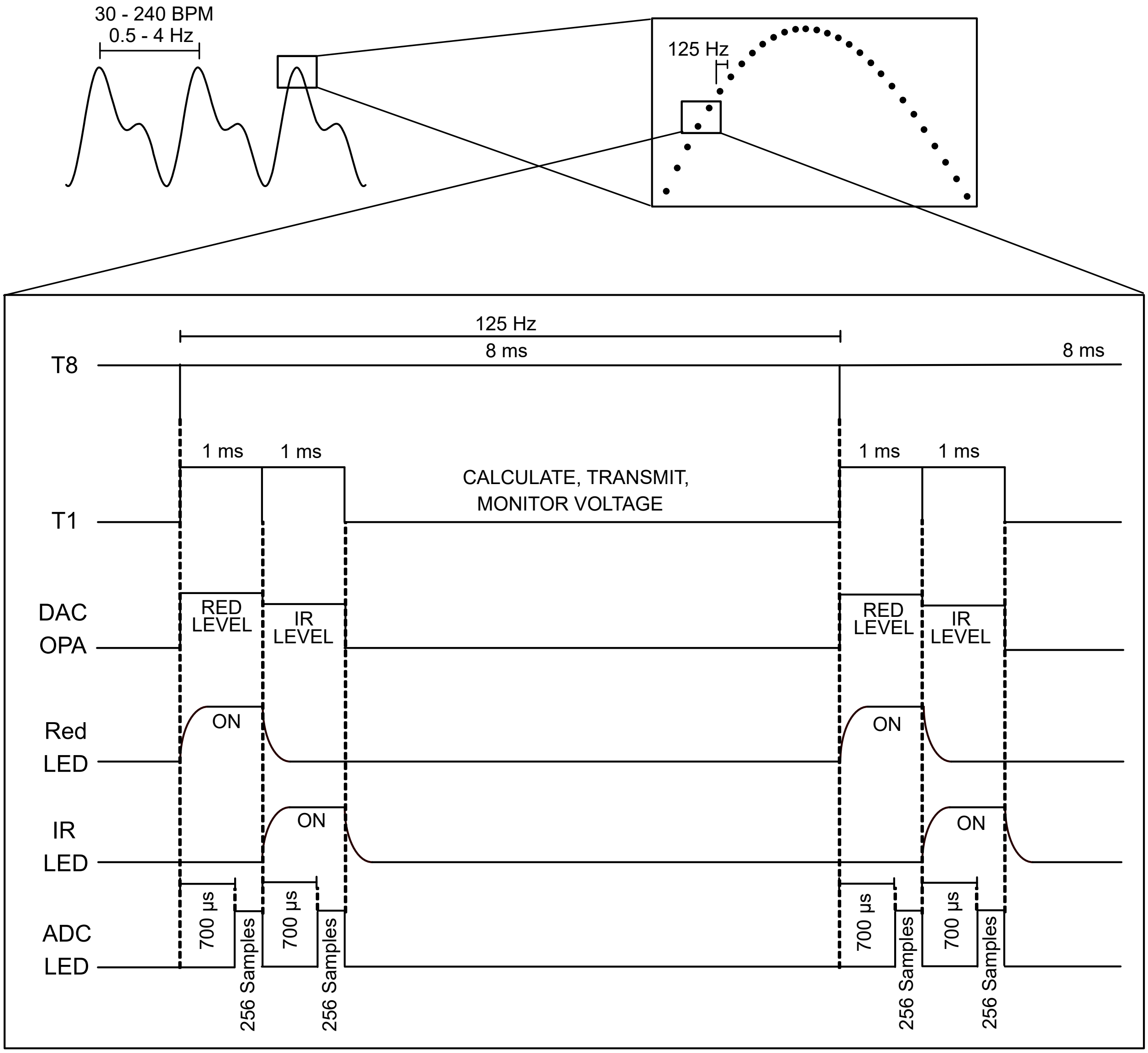


Figure 2-5. TIDA-010267 Timing Diagram

2.2.5.2 Oversampling and Digital Filtering to Increase Dynamic Range

The key features of the TIDA-010267 reference design lay in the excellent dynamic range which can be achieved through oversampling and filtering digitally. The high-speed 12-bit ADC of the MSPM0L1306 can be oversampled as selected by the user, increasing the bit count to 16. This allows the design to take advantage of an increased ENOB, and therefore an increased dynamic range. To further increase the ENOB of the ADC signal, a moving average FIR filter of adjustable magnitude is used to filter out ambient noise in this design. These methods of increasing dynamic range are highly effective because of PPG signals operate at such low frequencies. A closer look of the effect of oversampling on dynamic range is demonstrated in Section 3.

2.2.5.3 Calculating Vitals

Because the oversampled data contains a combined DC and AC signal, a simple digital low-pass IIR filter capable of isolating the DC signal is applied. The filter works by adding a small portion of the difference between the input and the last output value to the last output value to form the new output value. If there is a step change in the input, the output performs a correction to be the same as the input over a period of time. The rate of change is controlled by a programmable coefficient determined by the user. The TIDA-010267 uses a coefficient determined by experimentation. Algorithms that detect peaks and troughs in the AC signal of the PPG are used to note the period between signal peak, and thus, the period of the heartbeat. These same detections are used in conjunction with the DC isolation to calculate R and eventually $\%SpO_2$.

2.3 Highlighted Products

2.3.1 MSPM0L1306

MSPM0L130x microcontrollers (MCUs) are part of the highly-integrated, ultra-low-power 32-bit MSPM0 MCU family based on the enhanced Arm® Cortex®-M0+ core platform operating at up to 32-MHz frequency. These cost-optimized MCUs offer high-performance analog peripheral integration, support extended temperature ranges from –40°C to 125°C, and operate with supply voltages ranging from 1.62 V to 3.6 V. The MSPM0L130x devices provide up to 64KB embedded flash program memory with up to 4KB SRAM. These MCUs incorporate a high-speed on-chip oscillator with an accuracy up to ±1.2%, eliminating the need for an external crystal. Additional features include a 3-channel DMA, 16- and 32-bit CRC accelerator, and a variety of high-performance analog peripherals such as one 12-bit 1.68-MSPS ADC with configurable internal voltage reference, one high-speed comparator with built-in reference DAC, two zero-drift zero-crossover operational amplifiers with programmable gain, one general-purpose amplifier, and an on-chip temperature sensor. These devices also offer intelligent digital peripherals such as four 16-bit general purpose timers, one windowed watchdog timer, and a variety of communication peripherals including two UARTs, one SPI, and two I2Cs. These communication peripherals offer protocol support for LIN, IrDA, DALI, Manchester, Smart Card, SMBus, and PMBus.

3 Hardware, Software, Testing Requirements, and Test Results

The key performances of TIDA-010267 were tested in a TI lab. The equipment used, test processes, and results are described in this section.

3.1 Hardware Requirements

Table 3-1. TIDA-010267 Hardware Requirements

EQUIPMENT	DESCRIPTION
TIDA-010267	Assembled demonstration with LEDs in clip form
TI XDS110 JTAG debug probe	Debug probe for programming MSPM0L1306
FTDI TTL-234X-3V3	USB to UART cable with +3.3 V signal level
2.5-V voltage reference	DC signal within ADC range to test ADC performance

Figure 3-1. TIDA-010267 Assembled Demonstration for Testing

3.2 Software Requirements

3.2.1 TI GUI

Access the *TI Pulse Oximeter Demo GUI* from the TI Developer Zone Gallery.

By selecting the Pulse Oximeter Demo GUI, a new tab opens displaying information about the TIDA-010267 and an additional tab in the GUI is available to access the data graphs and vital signs.

3.2.2 CCS Project

The TI Pulse Oximeter Demo CCS Project can be used by navigating to the latest MSPM0 SDK folder (file path mspm0_sdk_1_10_00_05\examples\nortos\LP_MSPM0L1306\demos) via the *Project Tab* and then selecting *Import CCS Projects*.

The CCS Project allows the user to modify parameters according to desired specifications and features for the demonstration.

3.2.3 Analog Engineers Calculator

To download the calculator, visit TI Analog Engineers Calculator.

The calculator has a wide variety of analog simulation and data analysis tools for ADCs and OPAs and allows the user to experiment with data and parameters to fit the needs of the design. The Data Analysis Tool Kit under *Data Convertors* is used to graph the performance of the ADC with the TIA OPA input.

3.3 Test Setup

Figure 3-2 demonstrates the UART and debug connections necessary to control code parameters and display serial data.

The XDS1100 Debug Probe can connect to the adapter on the PCB using the 10-pin JTAG connector. Note the orientation illustrated in Figure 3-2.

The UART connection is established using the black, orange, and yellow wires and the UART-to-USB cable.

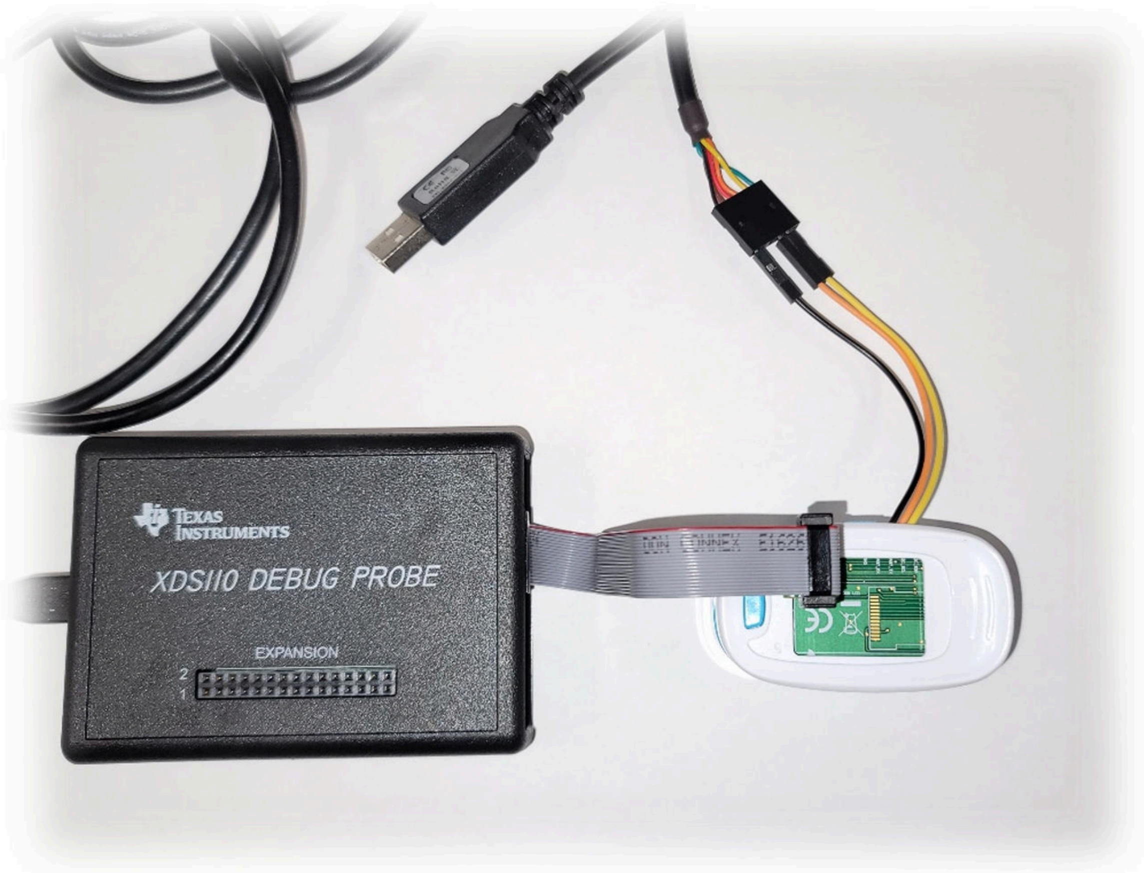


Figure 3-2. TIDA-010267 Pulse Oximeter Demonstration Connections for Testing

3.4 Test Results

Connecting the Pulse Oximeter Demo to the computer and running the GUI graphs generates Figure 3-3. Clean signals are displayed on the graphs and an accurate 99% SpO2 and 62 BPM of the user are displayed.

The following graphing options are included in the software:

- Oversampled Waveform Graph: demonstrates the full-scale range of the ADC with oversampling to 16 bits to portray both the DC and AC components.
- IR Waveform Graph: demonstrates a magnified perspective of the AC component of the IR signal to emphasize a high level of clarity
- Red Waveform Graph: demonstrates a magnified perspective of the AC component of the IR signal to emphasize a high level of clarity

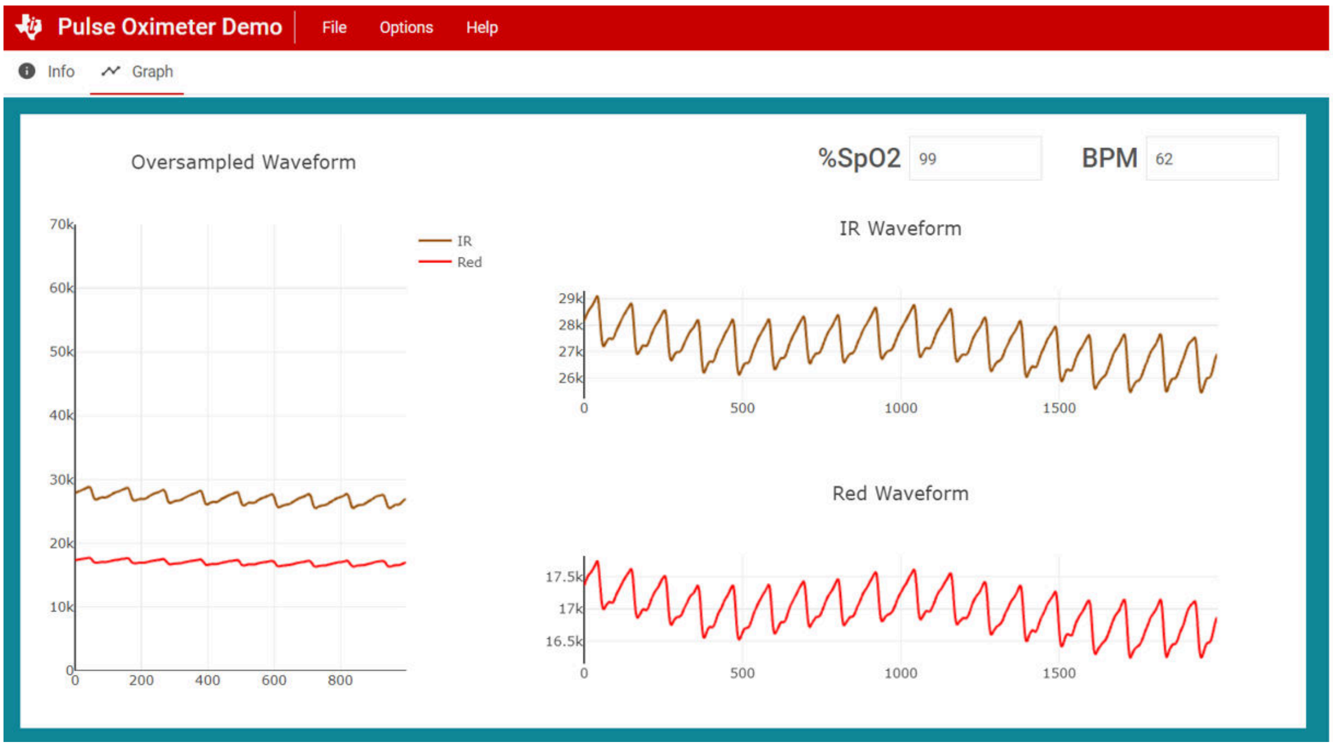


Figure 3-3. TIDA-010267 Pulse Oximeter Demo GUI for Testing and Display

Connecting the 2.5-V Voltage Reference to the OPA + ADC input for testing allows the user to serially capture the data for analysis on the computer, generating Figure 3-4 and Figure 3-5. A 15.3-bit ENOB is achieved with > 90-dB dynamic range, shown as a low-noise floor and low-deviation histogram, respectively.

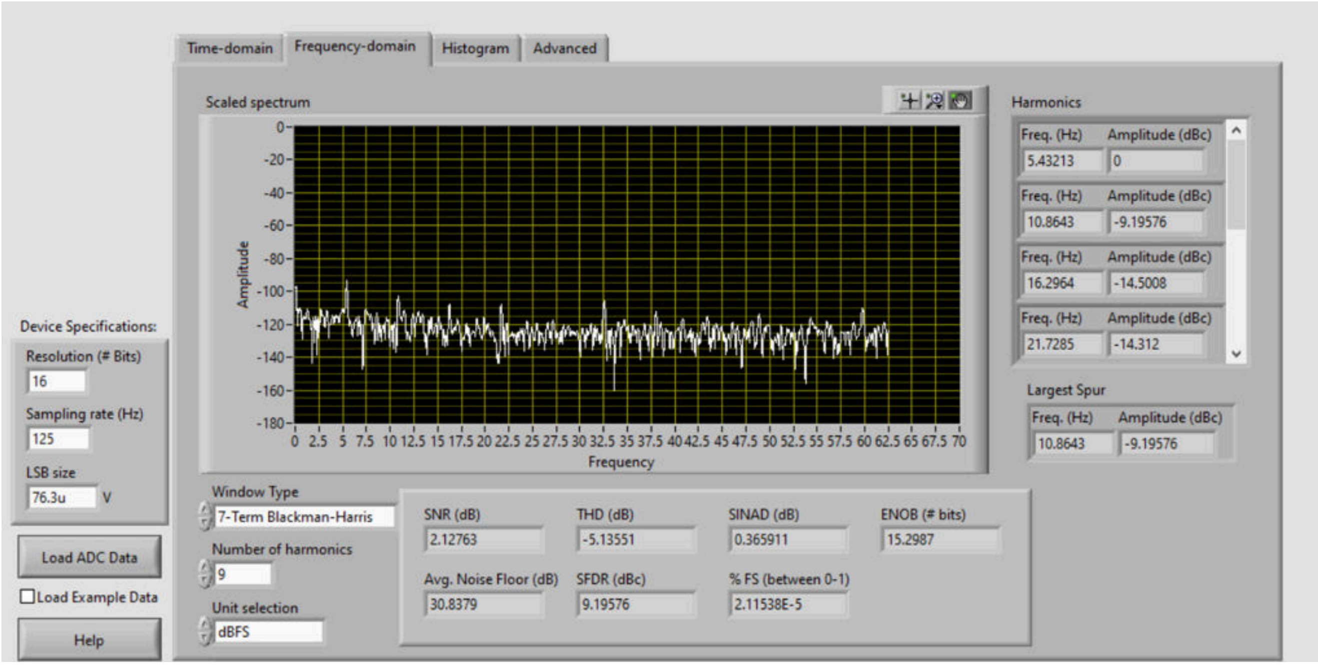


Figure 3-4. MSPM0L1306 16-bit Oversampled Frequency-Domain Noise Graph

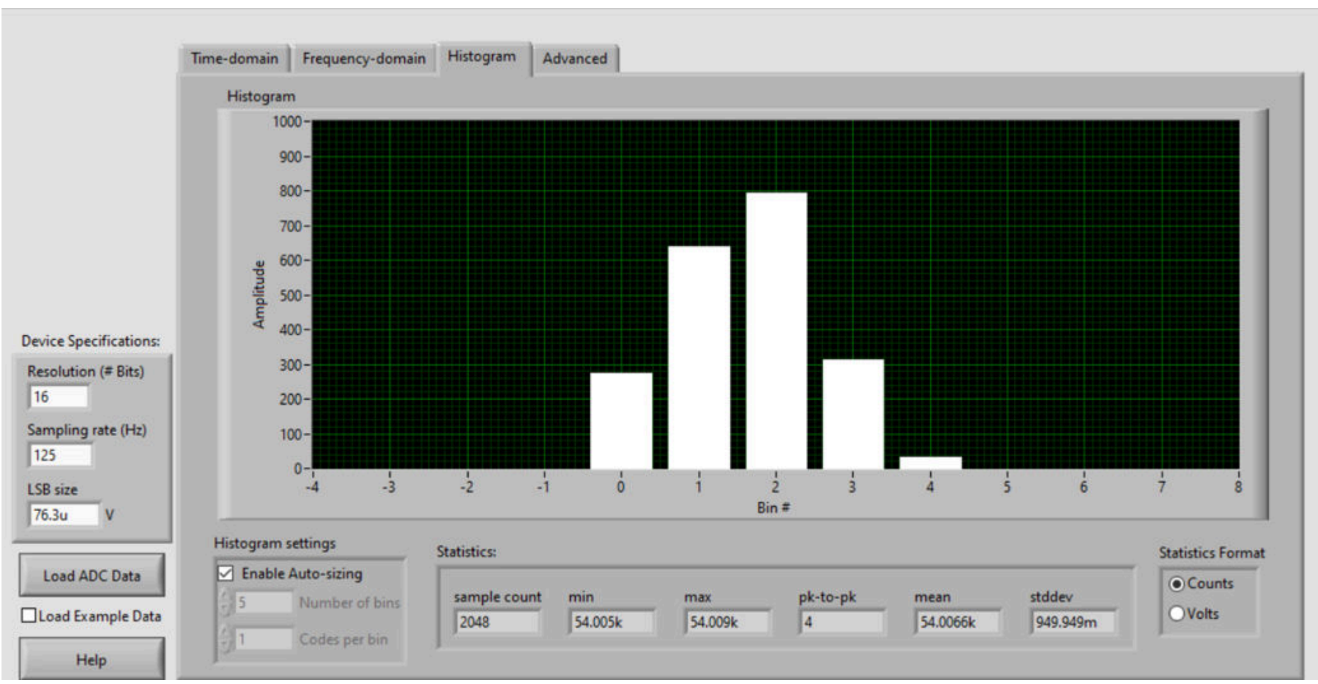


Figure 3-5. MSPM0L1306 16-bit Oversampled Frequency-Domain Noise Histogram

4 Design and Documentation Support

4.1 Design Files

4.1.1 Schematics

To download the schematics, see the design files at TIDA-010267.

4.1.2 BOM

To download the bill of materials (BOM), see the design files at TIDA-010267.

4.2 Tools and Software

Tools

Code Composer Studio™	Code Composer Studio is an integrated development environment (IDE) for TI's microcontrollers and processors. Code Composer Studio comprises a suite of tools used to develop and debug embedded applications. Code Composer Studio is available for download across Microsoft® Windows®, Linux®, and macOS® desktops. This product can also be used in the cloud by visiting the TI Developer Zone.

Software

TIDA-010267-MSPM0L130x-FW	With this downloadable firmware, the onboard MSPM0L1306 on the TIDA-010267 reference design allows for a single-chip, low-cost pulse oximeter design using integrated analog blocks that demonstrates PPG waveforms and vitals measurements.

4.3 Documentation Support

1. Texas Instruments, *MSPM0L130x Mixed-Signal Microcontrollers* data sheet
2. Texas Instruments, *Low-cost pulse oximeter and blood pressure monitor with Arm® Cortex®-M0+ MCUs* video
3. Texas Instruments, *Simplifying Pulse Oximeter Designs With Low-Cost Highly Integrated MSPM0 MCUs* application brief
4. Texas Instruments, *Single-Chip Pulse Oximeter Designs Based on MSP430FR2355* application report

4.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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