Pulse Oximeter - Standard

AN2313

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Application Note Abstract

The percentage of arterial blood (or haemoglobin (Hb)) saturated with oxygen to provide anaesthesia helps to determine the effectiveness of a patient's respiratory system, and to diagnose various illnesses. A Pulse Oximeter is a non-invasive device used to measure the percentage of haemoglobin saturated with oxygen and to measure heart rate. This application note describes a Pulse Oximeter, which is useful in medical, sports training, and home appliance applications

Introduction

The Pulse Oximeter operation is based on measuring the absorption of red and infrared light that passes through a patient's finger or ear lobe by using light sensors. Haemoglobin that transports oxygen (oxy-haemoglobin) absorbs infrared wavelength (800-940 nm) of light and haemoglobin that does not transport oxygen (deoxy-haemoglobin) absorbs visible red wavelength (600-700 nm) of light. Backgrounds such as fluid, tissue, and bone are factored out of the measurement by monitoring the steady state of absorption from bone tissue, venous blood, and arterial blood (see Figure 1). LEDs are used as the light source and are sequentially pulsed at a fast rate. During a heartbeat, blood volume increases and the AC component of the photodetector's current is used to calculate the absorption of oxy and deoxy-haemoglobin.

Principles of Operation

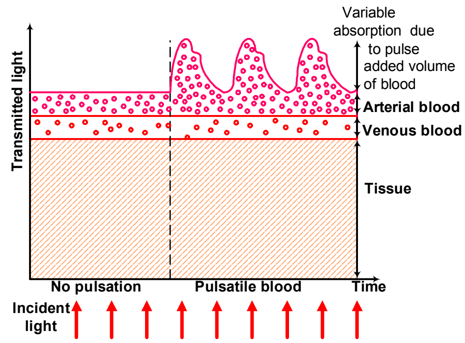
The Pulse Oximeter performs mathematical calculations based on the Beer-Lambert law to determine the percentage of blood that is saturated with oxygen:

$$I = I_0 \exp\left(\alpha(\lambda) c\, d\right) \qquad \text{Equation 1}$$

I is the intensity of light that comes out from the medium. I_0 is the intensity of incident light that enters the medium. $\alpha(\lambda)$ is a wavelength-dependent absorbance coefficient. d is the path length through the medium and c is the analyte concentration.

The properties of Beer-Lambert's law are valid even if more than one substance absorbs light in the medium (see Figure 1).

Figure 1. Light Passing through the Substances of a Finger



The total light attenuation can be described by four different component absorbancies:

1. Oxy-haemoglobin in the blood (concentration c_{HbO_2}, molar absorbance $\alpha_{HbO_2}(\lambda)$, and effective path length d_{HbO_2}).
2. Deoxy-haemoglobin in the blood (concentration c_{Hb}, molar absorbance $\alpha_{HbO_2}(\lambda)$, and effective path length d_{Hb}).
3. Specific absorbancies that are not from the arterial blood (concentration c_x, molar absorbance $\alpha_x(\lambda)$, and effective path length d_x).
4. All other non-specific sources of optical attenuation, combined as A_0 that include light scattering, geometric factors, and characteristics of emission and detection elements.

Each absorber contributes its part to the total absorbance:

$$A = \ln\left(\frac{I}{I_0}\right) = \alpha_{HbO_2}(\lambda)c_{HbO_2}d_{HbO_2} + \alpha_{Hb}(\lambda)c_{Hb}d_{Hb} + \alpha_x(\lambda)c_xd_x + A_0 \quad \text{Equation 2}$$

To find oxygen saturation, first calculate the ratio *R* of pulse-to-constant proportions at different wavelengths:

$$R = \frac{AC_{RED}/DC_{RED}}{AC_{IR}/DC_{IR}} \quad \text{Equation 3}$$

AC_{RED} and AC_{IR} are AC components of the red and infrared light sources, respectively. DC_{RED} and DC_{IR} are DC components of the red and infrared light sources, respectively.

In practice, a clinical empirical formula for the Oxygen Saturation Percentage (SpO_2) is used:

$$S = \mathbf{a} - \mathbf{b}R \quad \text{Equation 4}$$

a and **b** are coefficients that are determined when the Pulse Oximeter is being calibrated.[1]

Pulse Oximeter Block Diagram

Figure 2 on page 3 depicts the Pulse Oximeter block diagram. The device uses a modulated carrier technique in the sensor signal processing to increase noise resistance. The carrier generator forms the modulation signal, which drives the infrared and red LEDs. The LED switch switches the LEDs with a frequency that is equal to the ADC sampling frequency.

The received light is converted to an electric signal by a photodiode and then amplified. The bias generator removes the low frequency noise (any constant level or AC-powered, lamp-induced) from the photodiode signal. It also provides stable bias voltage, regardless of external light, together with high input impedance to modulate the photodiode current frequency.

The amplified signal from the photodiode is rectified by a synchronous amplitude demodulator. The demodulator reference signal is set to the modulation signal. A low pass filter (LPF) is necessary to remove the modulation signal. The LPF output is sampled directly by the integrating ADC.

The ADC data stream process is implemented in firmware. It is divided into two paths: IR wave (infrared LED) and RED wave (red LED) that alternate with the ADC sampling rate. The ADC sampling rate equals 50 Hz. In addition, the digital LPFs remove the noise on the output signal. The high pass filters (HPF) independently remove the DC component of the IR and RED waves from the LPF output signal. The differentiator separates the pulse beats of the IR wave. The pulse beats are detected by a smart peak detector with a threshold level that is automatically adjusted to increase the noise resistance and reliably handle signals with different pulsation amplitudes.

Using the IR and RED waves, the SpO_2 calculating algorithm determines the ratio *R* that gives the Oxygen Saturation value *S* using Equations (3) and (4).

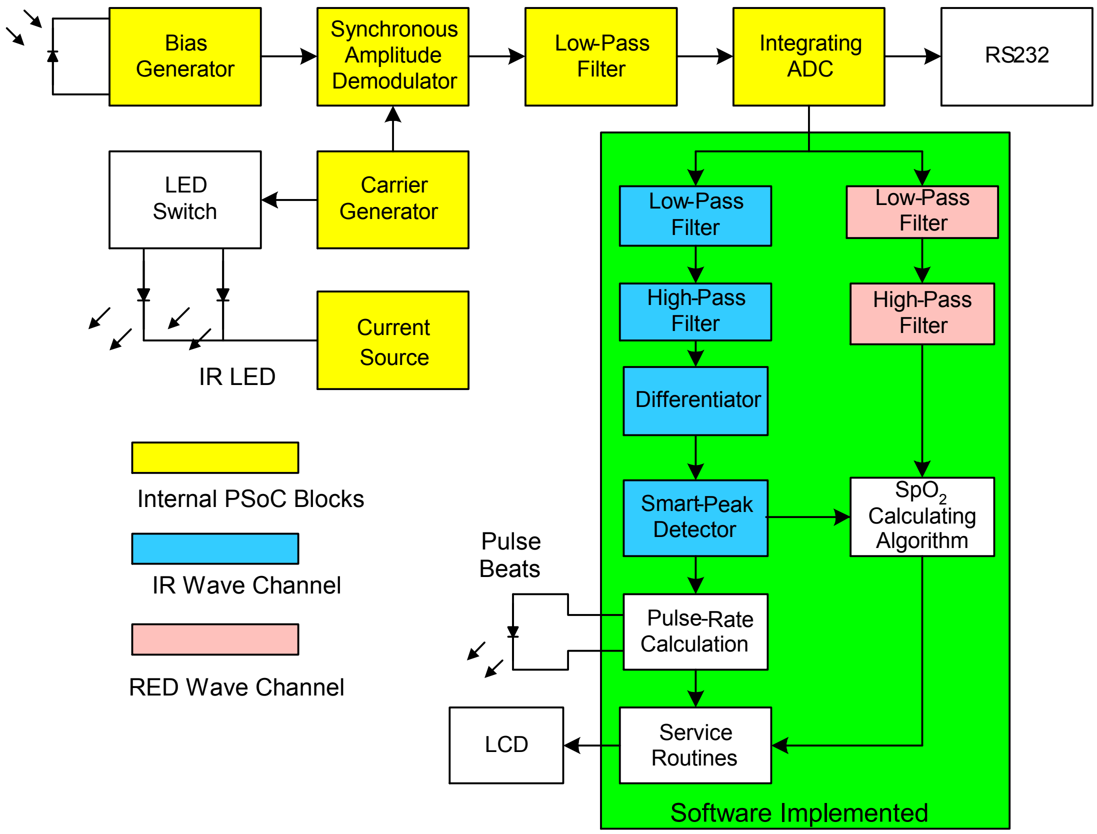
The software calculates the pulse rate in beats per minute and provides Pulse Oximeter status information through the graphical interface. Such information includes pulse rate, SpO_2 level, error conditions, operation mode, and so on.

To process external pulse wave signals and for debug purposes, the raw unfiltered ADC data can be sent through a RS232 port.

Table 1. Pulse Oximeter Specifications

Item	Item Value
Pulse Measurement Method	Optical, using light absorption modulation through capillary filling pulsations.
SpO_2 Measurement Method	Optical, using red (660 nm) and infrared (940 nm) LEDs to measure the differential absorption of light by oxygenated and reduced haemoglobin.
Power Supply Voltage	5V (regulated).
Power Consumption	60 mA.
Measured Pulse Range	40 - 260 beats-per-minute.
Measured SpO_2 Range	0 - 100%.
Measurement Time	11 pulse intervals or 3 ÷15 sec.
Pulse Calculation Method	Measuring time interval between adjacent beats.
Display Type	16x2 text LCD.
Service Features	LED flashes when the beat is detected. Pulse wave signal transmission to PC via RS232 interface.

Figure 2. Pulse Oximeter Block Diagram

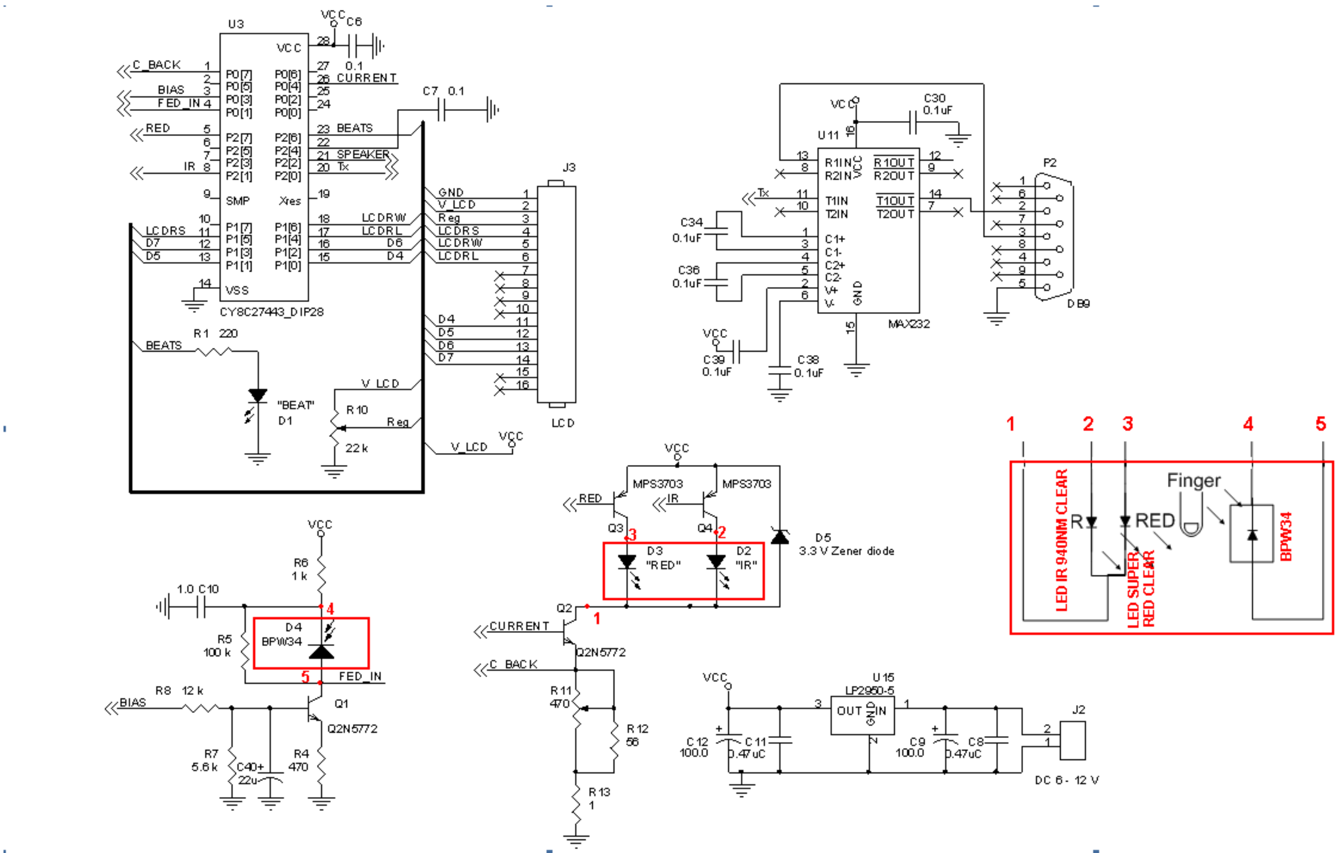


Device Schematic

The Pulse Oximeter schematic is shown in Figure 3 on page 4. The block diagram (Figure 2) illustrates that the hardware functions are integrated into the PSoC® device, CY8C27433. Q1 is the voltage-to-current converter, which forms the DC bias level for photodiode D4. The bias generator has low impedance for constant current or low frequency signals, and suppresses the noise signals caused by various external light sources. For the modulation frequency signals, the impedance is determined primarily by R5. The Q1 base signal is formed by a PSoC programmable gain amplifier (PGA) User Module, which amplifies the photodiode signal. The PGA output voltage is determined by PGA reference, which is connected to AGND in this design.

The bias generator helps to reduce the required photodiode signal gain level, decrease the LED drive current, and deplete noise in the output waveform. D_2 and D_3 are the modulation infrared and red LEDs respectively. D1 is the Pulse Oximeter LED that flashes every time a beat is detected. The infrared and red LEDs are switched by PNP transistors Q3 and Q4. Q2 is the regulator transistor of the programmed current source. Using the resistor R11 you can adjust the current through the infrared and red LEDs. The 3.3V Zener diode guarantees the current source remains in a linear range when both LEDs are switched off. The calculated pulse rate and oxygen saturation are displayed on the low cost, text LCD J3. Probe is constructed using IR, RED LEDs of correct wavelength, and Pin Photodiode as shown in Figure 3 on page 4.

Figure 3. External Hardware Schematic



PSoC Internals

The PSoC internal structure is illustrated in Figure 4 on page 5. The bias generator PGA is placed in ACB00. A bias generator is described in detail in the application note AN2158, “Optical PulsOmeter with PSoC.”

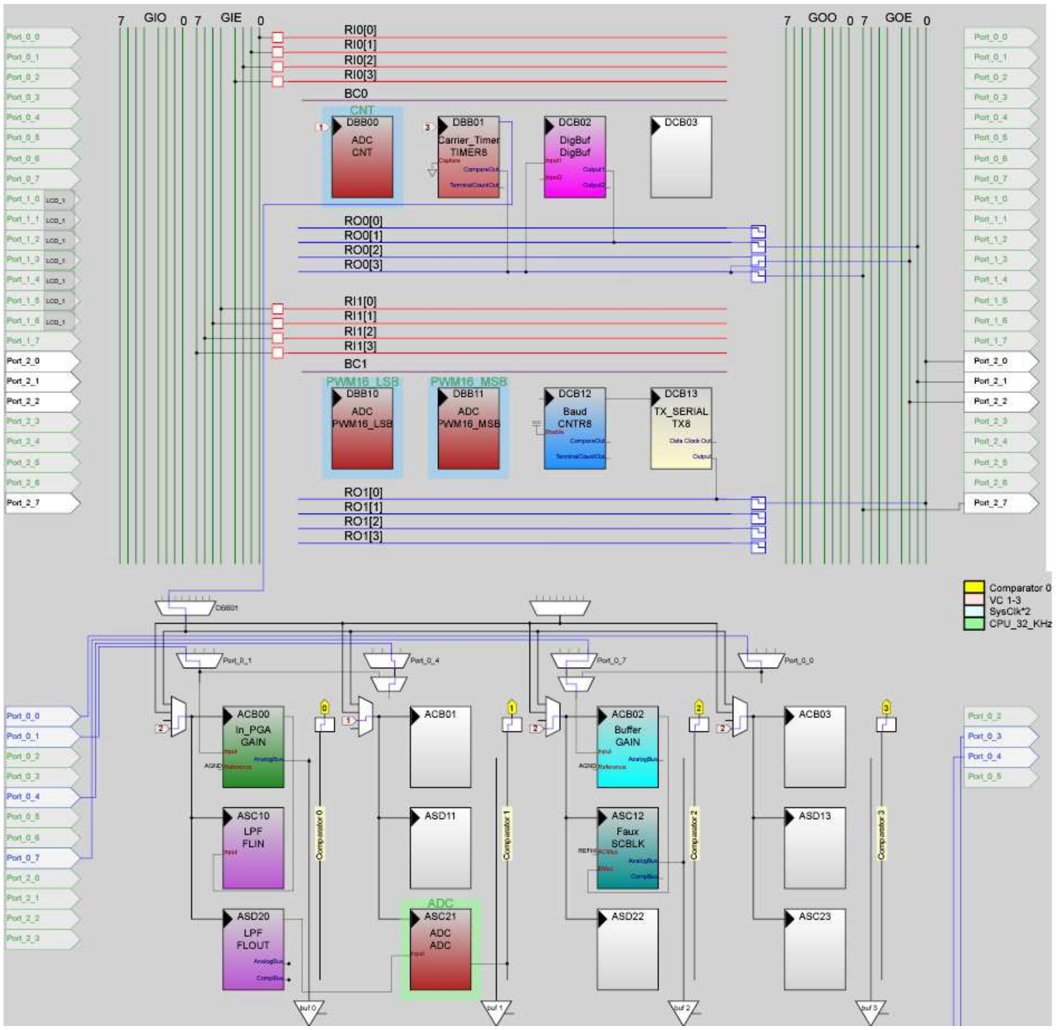
The amplifier is connected to the LPF, which is placed in ASC10 and ASD20. The filter plays two roles: it is used as a synchronous rectifier (switched capacitor block ASC10) and an LPF. The rectifier reference comes from GlobalOut_Even1. The filter also amplifies the signal for better use of the ADC dynamic range.

The LPF output is connected to the ADC input. In this design, the incremental ADC is used and its resolution is set to 13 bits. The modulation frequency is set to 5 kHz. ADC integration time is 20 mS, and the ADC sample frequency is very close to 50 Hz.

The serial transmitter placed in DCB13 along with the baud-rate timer placed in DBB12, are used to transmit ADC sample streams (for debugging) and other information to the PC. They can be omitted in the production release of the Pulse Oximeter. The timer, placed in DBB01, forms the modulation signal, which drives transistors Q3 and Q4. The timer clock source is VC3.

The programmable current source is used to set the LEDs to a stable current. It consists of blocks ACB02 and ASC12, external pass transistor Q2, and current setting resistor R11. Because the sensitivity of the photodiode is different for infrared and red LEDs, the software sets the different values of the current through the LEDs. This balances the amplitudes of received signals for infrared and red channels. This current source is described in detail in the application note AN2203, “Programmable Analog High Current Source. PSoC Style.”

Figure 4. PSoC Internal User Module Configuration



Pulse Oximeter Software

The Pulse Oximeter software performs the following tasks:

- Reads and digitally filters ADC data
- Calculates pulse rate and SpO2
- Displays values on the LCD

Figure 5 shows the real time, signal processing algorithm. The ADC samples are divided into IR and RED streams and independently filtered by a second order IIR LPF and a first order HPF. Note that after every ADC sample, the LEDs are switched in the following manner: the IR LED is switched on, the red LED is switched off, and vice versa. Therefore, each channel sampling frequency is only 25 Hz.

The LPFs have the following transfer function with the cut-off frequency at 3 Hz:

$$H(z) = \frac{0.0625(1+z^{-2}) + 0.125z^{-1}}{1 - 0.75z^{-1} + 0.25z^{-2}} \qquad \text{Equation 5}$$

The HPFs have the transfer function with the cut-off frequency at 0.5 Hz:

$$H(z) = \frac{0.5(1-z^{-1})}{1 - 0.9375z^{-1}} \qquad \text{Equation 6}$$

To get the first derivative of the pulse signal, which is used to calculate pulse rate, the first order IIR high pass filter with cut-off frequency Fc = 9 Hz is used:

$$H(z) = \frac{0.5(1-z^{-1})}{1 - 0.125z^{-1}} \qquad \text{Equation 7}$$

To implement these equations in 'C', in fixed-point representation, you must scale the filter's coefficients by 65536 and then verify if the filters remain stable (all poles lie within the unit circle of z-plane). The quantized filter is stable if:

$$\lim_{n\to\infty} h(n) = 0 \qquad \text{Equation 8}$$

h(*n*) is the impulse response of the quantized filter. The MATLAB® tools were used to study the filter stability.

The filters are implemented in 'C' using the following expressions.

Second-order IIR LPF (Fc = 3 Hz):

```
diff1 = yn_1<<16;

y = ( (((x + xn_2)<<16)>>4) +
((xn_1<<16)>>3) + (diff1>>1) + (diff1>>2) -
((yn_2<<16)>>2))>>16;

xn_2=xn_1;

xn_1=x;

yn_2=yn_1;

yn_1=y;
```

First-order IIR HPF (Fc = 0.5 Hz):

```
diff1 = y_hpf_IR_1<<16;

y = ((((x - x_hpf_IR_1)<<16)>>1) +
(diff1>>1) + (diff1>>2) + (diff1>>3) +
(diff1>>4)) >> 16;

x_hpf_IR_1 = x;

y_hpf_IR_1 = y;
```

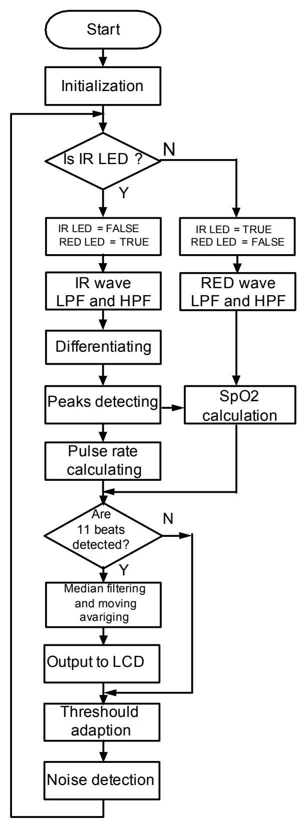
Differentiator (first-order IIR HPF with Fc = 9 Hz):

```
y = ((((x - x_hpf1_1)<<16)>>1) +
((y_hpf1_1<<16)>>3)) >> 16;

x_hpf1_1 = x;

y_hpf1_1 = y;
```

The division or scaling of 65536 is performed by shifting 16 bits to the right.

The differentiated infrared signal (see Figure 6 (b) on page 8) is used for beat detection. When the absolute magnitude of the differentiated signal is higher than the threshold value, the beat is detected and the time interval between beats is calculated.

Figure 5. Real Time, Pulse Calculation Algorithm



The SpO_2 is calculated each time a beat is detected. The calculation algorithm includes minimum and maximum estimates of infrared and red waves and calculates the SpO_2 using Equations (3) and (4). The value of SpO_2 is then passed through the fourth order moving average filter to reduce possible fluctuations.

After detecting 11 beats, the array of 11 time intervals is passed through a median filter that yields the duration value of time-between-beats integrated over the 11 samples. This operation is also performed with an array of SpO_2 values. The value is then passed through the second order moving average filter, and the pulse rate is scaled to units of beats-per-minute and displayed on the LCD.

To reduce detection of false beats after every detected beat, the algorithm performs automatic threshold level adjustments and noise detection during a 320-msec search window:

- The maximum of the absolute value is searched in an interval of t_1 = 200 ms after the detected beat and the threshold value is updated with 0.75*max(abs(E)), where E is the infrared wave.
- The threshold value is decreased incrementally every 200 ms until a lower limit is reached.
- If during an interval of 200 to 240 ms (t2) following the last beat detection, the abs(E) is greater than (threshold value), then noise is detected and the time interval measurement is restarted.

PC Debug Software

A program for viewing the infrared and red waves on a PC is developed and shows the generated signals displayed in Figure 6 on page 8. The software runs in Microsoft Windows. The source code is available with this application note.

Oximeter Calibration

The oximeter should be calibrated to provide accurate readings. The following calibration procedure is recommended:

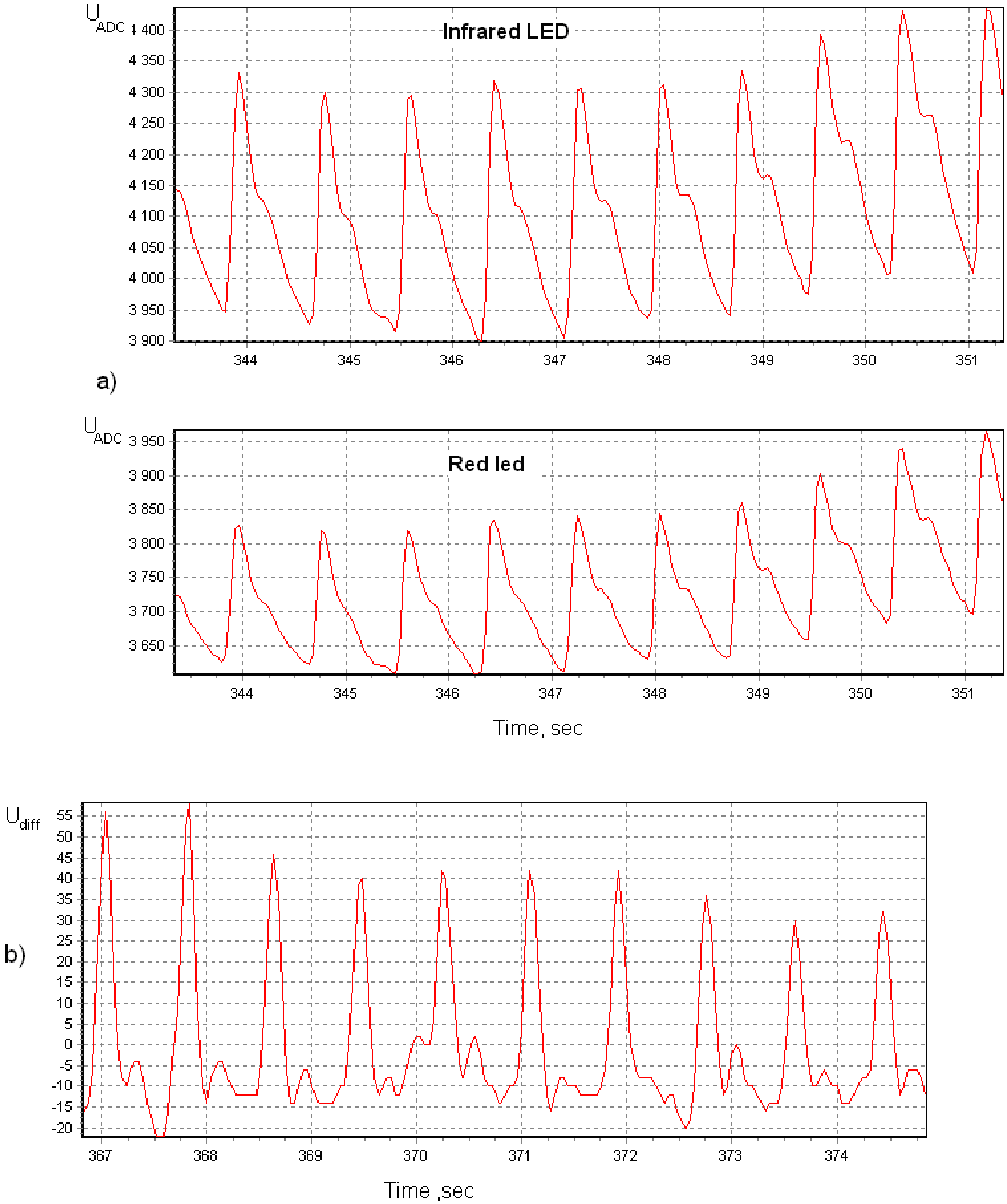
1. Place a transparent obstacle between the LEDs and photodiode. The obstacle simulates the minimum expected light absorption level by a finger for some intermediate SpO_2 value.
2. Set the LEDs' maximum current source reference value by setting the ASC12 block ACap parameter to 31.
3. Using the potentiometer R11, set the LEDs' current so that it prevents LPF saturation for both IR and red channels. The output of the LPF must be sampled by the ADC.
4. Balance the output level of the IR and red channels by setting the INFRARED_CURRENT and RED_CURRENT constants (in the *main.c* file) in inverse proportion to the measured absolute ADC value in the red and infrared channels. These constants are transferred to the ASC12 block ACap control register when measurements are taken in different light spectrum zones.
5. Now you need a calibrated SpO_2 simulator to find the **a** and **b** coefficients from Equation (4). By substituting different samples, which simulate the different SpO_2 value, the *R* code for the IR and red channels needs to be collected. Coefficients **a** and **b** can be determined by performing the linear fit of the *R* values using the least squares method [2] with the following equations:

$$a = \frac{\sum_{i=1}^{n} S_i \sum_{i=1}^{n} R_i^2 - \sum_{i=1}^{n} R_i \sum_{i=1}^{n} R_i S_i}{n\sum_{i=1}^{n} R_i^2 - \left(\sum_{i=1}^{n} R_i\right)^2} \qquad \text{Equation 9}$$

$$b = \frac{n\sum_{i=1}^{n} R_i S_i - \sum_{i=1}^{n} R_i \sum_{i=1}^{n} S_i}{n\sum_{i=1}^{n} R_i^2 - \left(\sum_{i=1}^{n} R_i\right)^2} \qquad \text{Equation 10}$$

S_i is the SpO_2 value measured by the SpO_2 simulator. R_i is the measured ratio *R* that corresponds to S_i. *n* is the number of measurements. These coefficients can be saved in the EEPROM for nonvolatile storage.

Figure 6. ADC Data Signal Processing in Pulse Oximeter
a) ADC Data from Infrared and Red LEDs, b) Differentiated Infrared Wave



Suggested Improvements

It is a good idea to generate a beep through the piezoelectric speaker after a detected beat. It is also possible to make the following improvements: Use of a flash card to log pulses and use of Cypress WirelessUSB technology to send infrared and red waves, measured SpO_2, and pulse rate values to the PC.

Summary

The Pulse Oximeter can be used in medical, sports training, and home appliance applications. Note that optical oximeters are not very accurate devices but are a good indicator of blood oxygen saturation and desaturation levels. This device provides correct readings when it is properly calibrated.

Devices used for medical diagnostic applications must undergo a rigorous documentation and qualification program to meet applicable medical safety and efficacy standards.

References

1. Dr SJ Fearnley. Pulse Oximetry. http://www.nda.ox.ac.uk/wfsa/html/u05/u05_003.htm
2. Numerical Recipes in C. http://www.nr.com

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Document History Page

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Revision	ECN	Submission Date	Orig. of Change	Description of Change
**	1448845	09/14/2007	SEG	Old application note added to the spec system.
*A	2856235	01/18/2010	KUK	Updated Device Schematic section. Modified Figure 3. Attached Pulse Oximeter side application.

In March of 2007, Cypress recataloged all of its Application Notes using a new documentation number and revision code. This new documentation number and revision code (001-xxxxx, beginning with rev. **), located in the footer of the document, will be used in all subsequent revisions.

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