![TEXAS INSTRUMENTS]

# A Single-Chip Pulsoximeter Design Using the MSP430

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## ABSTRACT

This application report discusses the design of non-invasive optical plethysmography also called as pulsoximeter using the MSP430FG437 microcontroller (MCU). The pulsoximeter consists of a peripheral probe combined with the MCU displaying the oxygen saturation and pulse rate on a LCD glass. The same sensor is used for both heart-rate detection and pulsoximetering in this application. The probe is placed on a peripheral point of the body such as a finger tip, ear lobe or the nose. The probe includes two light emitting diodes (LEDs), one in the visible red spectrum (660 nm) and the other in the infrared spectrum (940 nm). The percentage of oxygen in the body is worked by measuring the intensity from each frequency of light after it transmits through the body and then calculating the ratio between these two intensities. Project collateral discussed in this application report can be downloaded from the following URL: www.ti.com/lit/zip/SLAA274.

This application report uses the MOD-PULSE *Pulseoxmeter and Heart-Rate Monitor Using the MSP430FG439* development board by OLIMEX Ltd (http://www.olimex.com/dev/mod-pulse.html).

A revised version of this application is described in the application report *Revised Pulsoximeter Design Using the MSP430* (SLAA458).

## 1 Introduction

The Pulsoximeter is a medical instrument for monitoring the blood oxygenation of a patient. By measuring the oxygen level and heart rate, the instrument can sound an alarm if these drop below a pre-determined level. This type of monitoring is especially useful for new born infants and during surgery.

This application report demonstrates the implementation of a single chip portable pulsoximeter using the ultra low power capability of the MSP430. Because of the high level of analog integration, the external components can be kept to a minimum. Furthermore, by keeping ON time to a minimum and power cycling the two light sources, power consumption is reduced.

## 2 Theory of Operation

In a pulsoximeter, the calculation of the level of oxygenation of blood ($SaO_2$) is based on measuring the intensity of light that has been attenuated by body tissue.

$SaO_2$ is defined as the ratio of the level oxygenated Hemoglobin over the total Hemoglobin level (oxygenated and depleted):

$$SaO_2 = \frac{HbO_2}{\text{Total Hemoglobin}}$$

(1)

Body tissue absorbs different amounts of light depending on the oxygenation level of blood that is passing through it. This characteristic is non-linear.

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.

$$R' = \frac{\log(I_{ac})\lambda 1}{\log(I_{ac})\lambda 2} \qquad SaO_2 \; \alpha \; R'$$

(2)

Where $\lambda 1$ and $\lambda 2$ represents the two different wavelengths of light used.

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There are 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 $SaO_2$ 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    Circuit Implementation



**Figure 1. System Block Diagram**

Figure 1 depicts the system block diagram. The two LEDs are time multiplexed at 500 times per second. The PIN diode is therefore alternately excited by each LED light source.

The PIN diode signal is amplified by the built in operational amplifiers OA0 and OA1. The ADC12 samples the output of both amplifiers. The samples are correctly sequenced by the ADC12 hardware and the MCU software separates the infra-red and the red components.

The $SaO_2$ level and the heart rate are displayed on an LCD. The real time samples are also sent via an RS232 to a PC. A separate PC software displays these samples a graphic trace.

Apart from the MCU and four transistors, only passive components are needed for this design.

An off-the-shelf Nellcor-compatible probe 520-1011N is used. This probe has a finger clip integrated with sensors and is convenient to use. The input to the probe is a D-type 9 pin connector.

## 3.1 Generating the LED Pulses
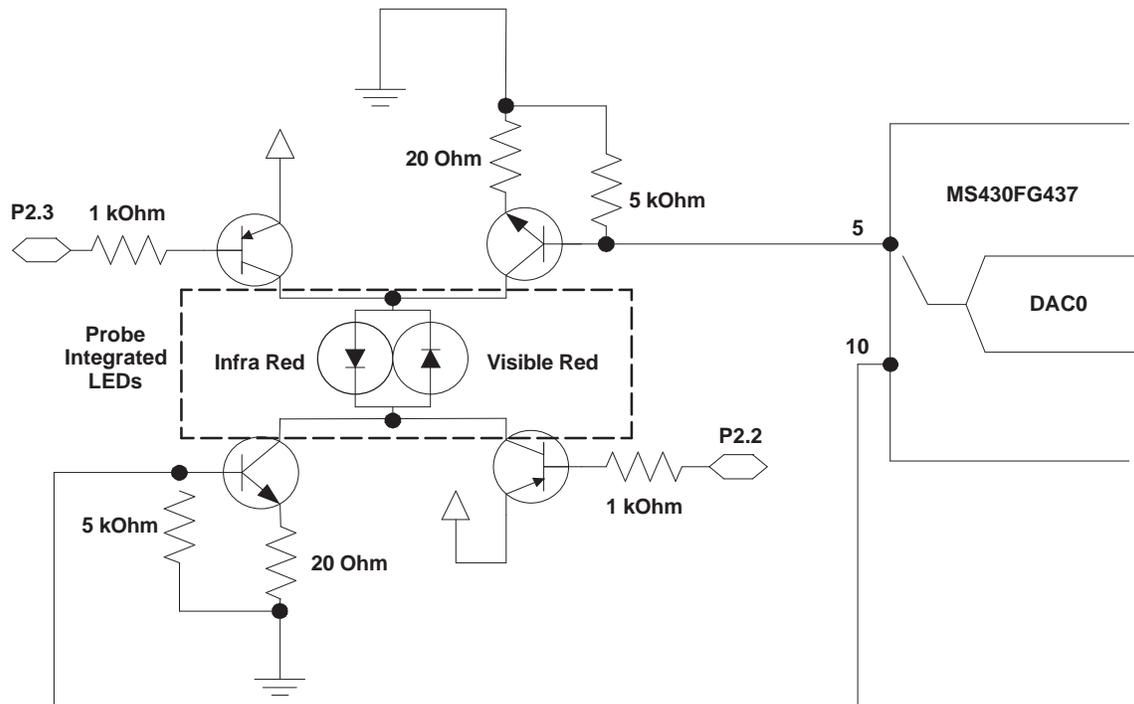


**Figure 2. LED Drive Circuit**

There are two LEDs, one for the visible red wavelength and another for the infrared wavelength.

In the Nellcor compatible probe, these two LEDs are connected back to back.

To turn them on, an H-Bridge arrangement is used. Figure 2 illustrate this circuit.

Port 2.3 and Port 2.2 drives the complementary circuit. A DAC0 controls the current through the LEDs and thereby its light output level.

The whole circuit is time multiplexed.

In the MSP430FG437 the internal 12-bit DAC0 can be connected to either pin 5 or pin 10 of the MCU through software control in the DAC control register. When a pin is not chosen to output the DAC0 signal, it is set to Hi-Z or low. The base of each transistor has a pulldown resistor to make sure the transistor is turned off when it is not selected.

## 3.2 Sampling and Conditioning the PIN Diode Signal
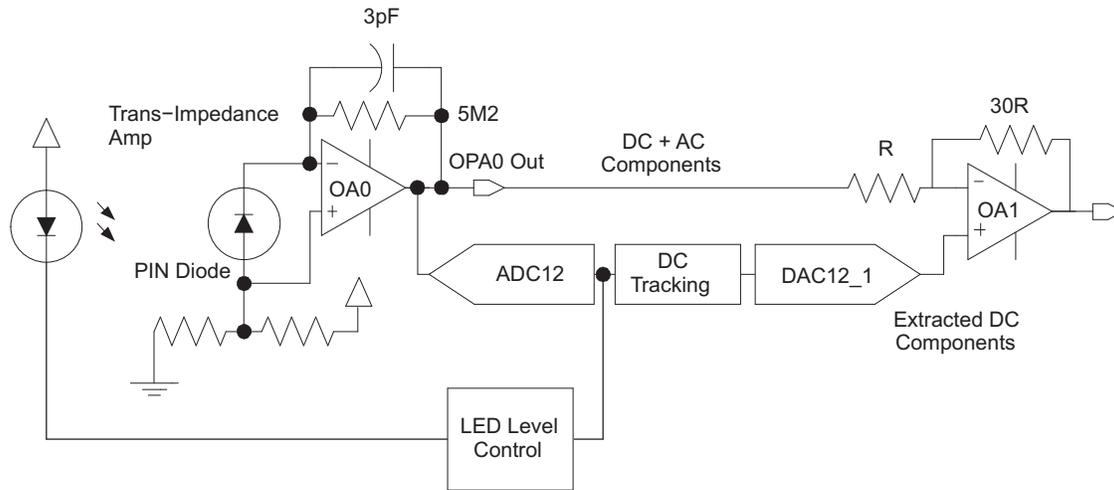
**Figure 3. Input Front End Circuit and LED Control**

The photo-diode generates a current from the received light. This current signal is amplified by a trans-impedance amplifier. OA0, one of the three built in op-amps, 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 signal coming out of OA0 consists of a large DC component (around 1 V) and a small AC component (around 10 mV pk-pk).

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 OA0 within a preset range using the circuit illustrated in Figure 2. The Normal Red and Infra Red 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 OA0 output is performed by the second stage OA1. The DC tracking filter extracts the DC component of the signal and is used as an offset input to OA1. As OA1 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 OA1 is also amplified and added to the output signal. This needs to be filtered off later on.

### 3.2.1 Time Multiplexing the Hardware
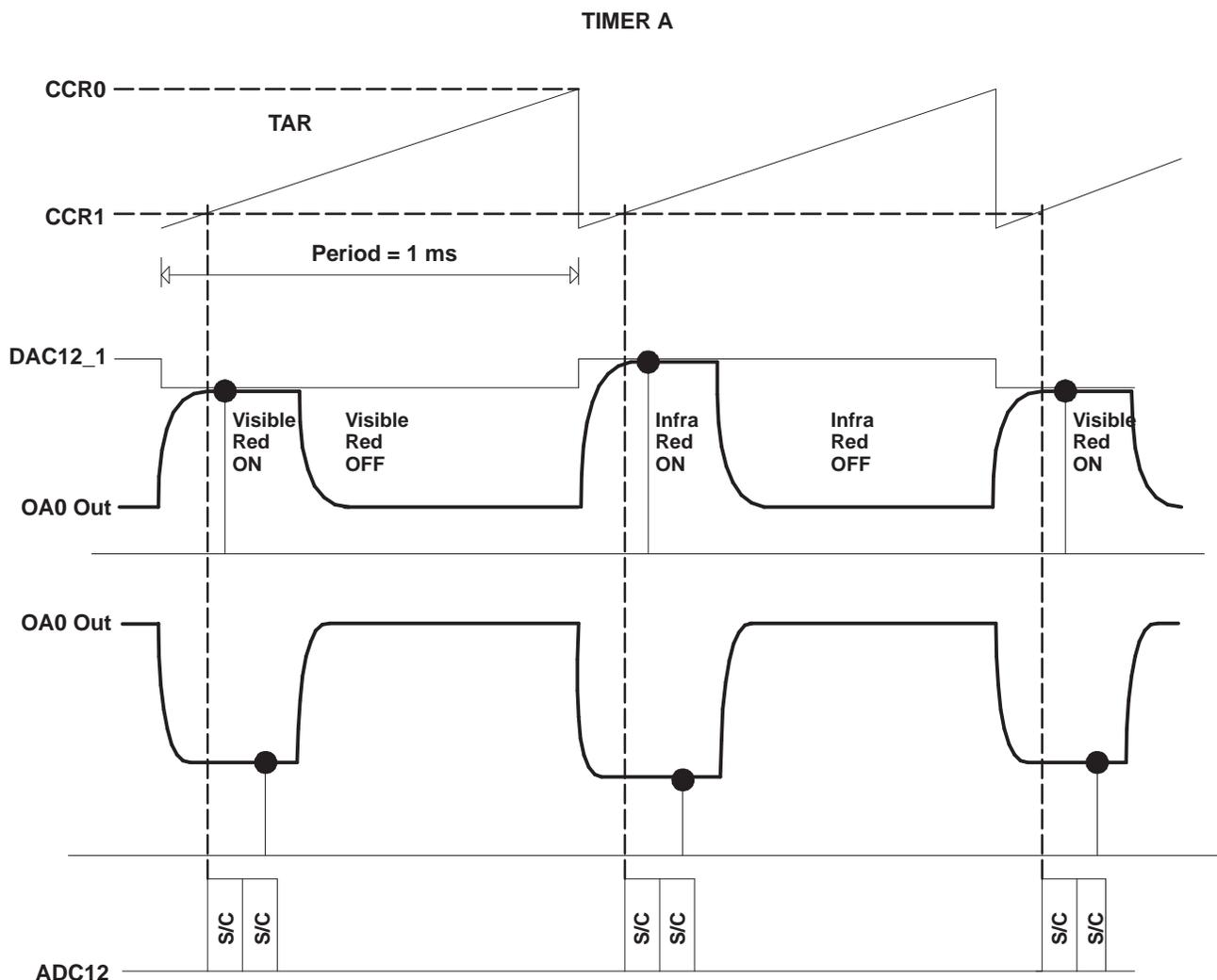
TIMER A



**Figure 4. Time Multiplexing the Hardware**

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

At the CCR0 interrupt, a new LED sequence is initiated with the following:

- The DAC12_0 control bit DAC12OPS is set or cleared depending on which LED is driven. Port 2 is set to turn on the corresponding LED.
- A new value for DAC12_0 is set to the corresponding light intensity level
- DAC12_1 is set to the DC tracking filter output for that particular LED.

Note that OA1 amplifies the difference between OA0 Out and DAC12_1.

As the intensity of the visible LED is adjusted, the DAC12_1 signal will become a straight line as the OA0 outputs for the two LEDs are equaled.

The ADC conversion is triggered automatically. It takes two samples, one of the OA0 output for DC tracking and one of the OA1 output, to calculate the heart beat and oxygen level. These two samples are taken one after the other using the internal sample timer by setting the MSC bit in the ADC control register.

To conserve power, at the completion of the ADC conversion an interrupt is generated to tell the MCU to switch off the LED by clearing DAC12_0.

## 3.3   Signal Conditioning of the AC Components
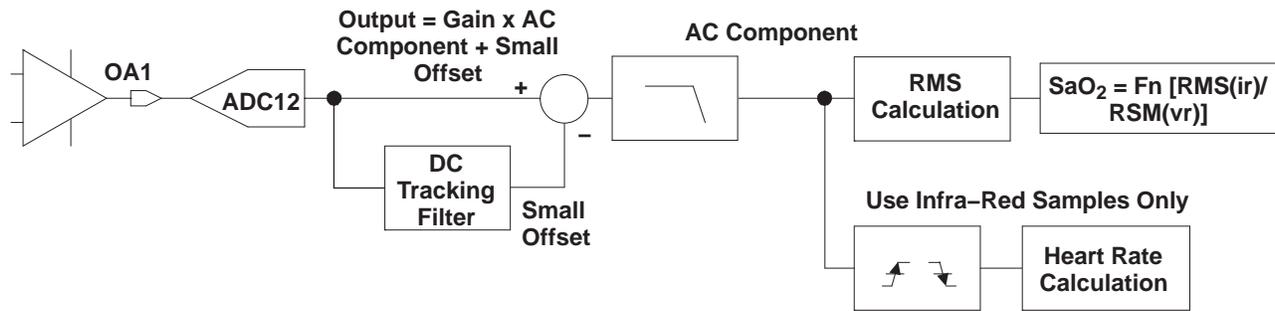


**Figure 5. Signal conditioning of the AC Components**

The output of OA1 is sampled by the ADC at 1000 sps. Alternating between the infra-red LED and the normal-red LED. Therefore each LED signal is sampled at 500 sps.

Samples of the OA1 output must be stripped of the residual dc. A high pass digital filter is impractical here, as the required cutoff frequency is rather low. Instead a IIR filter is used to track the dc level. The dc is then subtracted from the input signal to render a final true ac digital signal.

The sampled signal is digitally filtered to remove ambient noise at 50 Hz and above. A low pass FIR filter with a corner frequency of 6 Hz and -50 dB attenuation at 50 Hz and above is implemented.

At this stage the signal resembles the pulsing of the heart beat through the arteries.

### 3.3.1   The DC Tracking filters
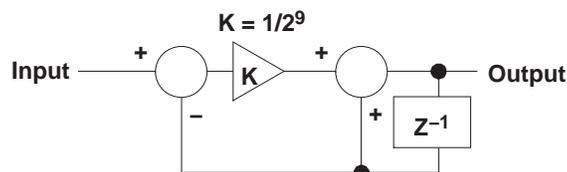


**Figure 6. Tacking Filter Block Diagram**

A DC tracking filter is illustrated in Figure 6.

This is an IIR filter. The working of this filter is best understood intuitively. The filter will add a small portion of the difference between its input and its last output value to its last output value to form the a 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.

To ensure there is sufficient dynamic range, the calculation is done is double precision, 32 bits. Only the most significant 16 bits are used.

## 3.4   Calculating the Oxygen Level and Heart Beat Rate

Because both LEDs are pulsed, traditional analog signal processing has to be abandoned in favor of digital signal processing.

The signal samples are low pass filtered to remove the 50/60 Hz noise.

For each wavelength of light, the DC value is removed from the signal leaving the AC part of the signal, which reflects the arterial oxygenation level. The RMS value is calculated by averaging the square of the signal over a number of heart beat cycles.

The DC measurement is continuously calculated by averaging the signals over a number of heart beat cycles.

The driving strength of each LED is controlled so that the DC level seen at the PIN diode meets a set target level with a small tolerance. By doing this for each LED, the final results is that the DC levels of these two LED match one another to within a small tolerance.

Once the DC levels match, then the $SaO_2$ is calculated by dividing the logs of the RMS values.

$$R' = \frac{\log(I_{ac})\lambda 1}{\log(I_{ac})\lambda 2} \qquad SaO_2 \ \alpha \ R'$$

(3)

The heart beat is measure by counting the number of samples in 3 beats, since the sampling rate is 500 sps. The heart beat per minute is calculated by:

$$\text{Heart beats per minute} = \frac{500 \times 60}{\left(\frac{\text{Samples Count}}{3}\right)}$$

(4)
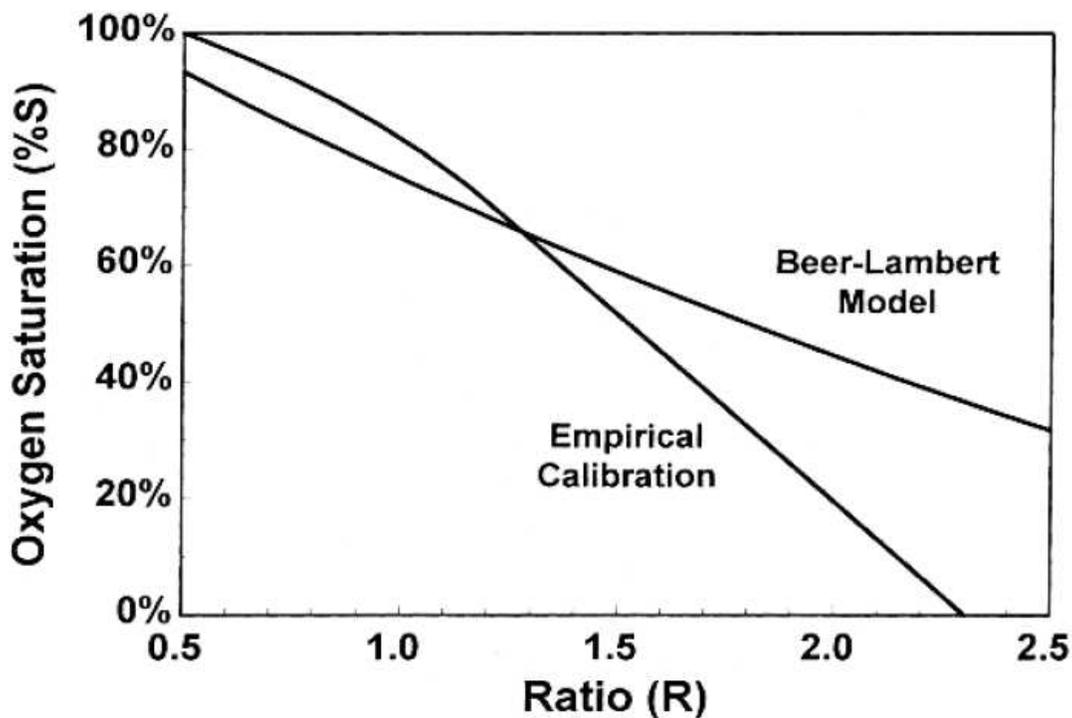


**Figure 7. Empirical and Theoretical R to SaO$_2$**

Figure 7 shows the difference between the empirical and theoretical R to $SaO_2$ curve.

As the Oxygen Saturation seldom drops below 80%, a linear relationship with a slight offset can safely be assumed.

## 4    Results
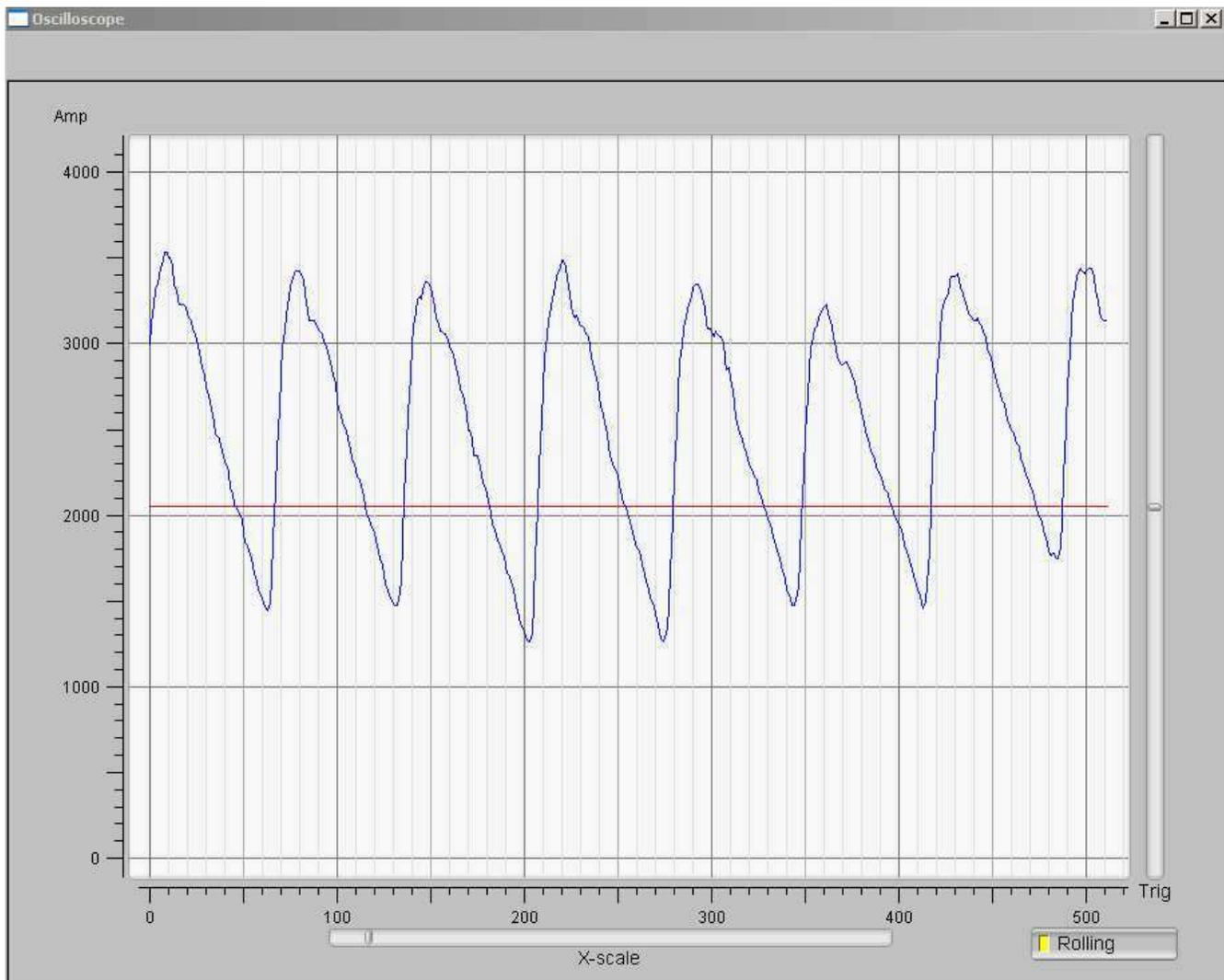


**Figure 8. Heart Beat Signal Output**

Figure 8 shows the captured Heart Beat signal from the board. This signal is output through the serial port to the PC at 115 Kbps. An open source application program scope.exe that runs on the PC is also available with this application notes.

The heart rate/minute is measured and displayed on the LCD.

The Oxygen Saturation percentage is also displayed.

# 5 Parts List

## Table 1. Parts List

| QTY | VALUE | PARTS |
|---|---|---|
| 2 | Tact switch | S1, S2 |
| 2 | 1n4148 | D4, D5 |
| 1 | DB9 | X2 |
| 1 | Jumper | JP1 |
| 1 | LCD | LCD1 |
| 1 | Red LED | LED3 |
| 3 | 4-pin header | SL1, SL2, SL5 |
| 1 | MAX3221 | U2 |
| 2 | MMBT2222 | T1, T2 |
| 1 | MSP430FG437 | U1 |
| 1 | LED 660nm, Kodenshi BL-23G | D2 |
| 1 | LED 940nm, Kodenshi EL-23G | D3 |
| 1 | Pin-diode, Kodenshi HPI-23G | D1 |
| 10 | 0.1uF | C1, C5, C6, C7, C8, C12, C13, C14, C15, C19 |
| 6 | 1kΩ | R16, R17, R18, R19, R27, R28 |
| 3 | 1uF | C3, C9, C20 |
| 1 | 3V battery | G1 |
| 1 | 3pF | C2 |
| 2 | 4.7nF | C16, C17 |
| 1 | 5.1MΩ | R3 |
| 3 | 5kΩ | R22, R24, R26[1] |
| 2 | 10kΩ | R13, R14 |
| 3 | 10uF | C4, C10, C11 |
| 1 | 15kΩ | R9 |
| 2 | 20Ω | R1, R2 |
| 1 | 32.768k | X1 |
| 1 | 47pF | C18[1] |
| 4 | 100Ω | R4, R5 |
| 3 | 100kΩ | R8, R15, R20 |
| 1 | 150kΩ | R25[1] |
| 3 | 300kΩ | R10, R11, R12 |
| 1 | Buzzer | SG2 |
| 1 | Nellcor compatible probe 520-1011N | |

[1] NOTE: If the internal feedback resistor ladder is used for OA1 (as implemented in the application source code), then these parts do not need to be populated: R25, R26 and C18.

# 6 References

- Medical Electronics, Dr. Neil Townsend, Michaelmas Term 2001
- *MSP430F4xx Family User's Guide* (SLAU056)

# 7    Schematic